

Strontium isotopic signatures of oil-field waters: Applications for reservoir characterization

Roger J. Barnaby, Gregg C. Oetting, and Guoqiu Gao

ABSTRACT

The $^{87}\text{Sr}/^{86}\text{Sr}$ compositions of formation waters that were collected from 71 wells producing from a Pennsylvanian carbonate reservoir in New Mexico display a well-defined distribution, with radiogenic waters (up to 0.710129) at the updip western part of the reservoir, grading downdip to less radiogenic waters (as low as 0.708903) to the east. Salinity (2800–50,000 mg/L) displays a parallel trend; saline waters to the west pass downdip to brackish waters.

Elemental and isotopic data indicate that the waters originated as meteoric precipitation and acquired their salinity and radiogenic ^{87}Sr through dissolution of Upper Permian evaporites. These meteoric-derived waters descended, perhaps along deeply penetrating faults, driven by gravity and density, to depths of more than 7000 ft (2100 m). The $^{87}\text{Sr}/^{86}\text{Sr}$ and salinity trends record influx of these waters along the western field margin and downdip flow across the field, consistent with the strong water drive, potentiometric gradient, and tilted gas-oil-water contacts.

The formation water $^{87}\text{Sr}/^{86}\text{Sr}$ composition can be useful to evaluate subsurface flow and reservoir behavior, especially in immature fields with scarce pressure and production data. In mature reservoirs, Sr isotopes can be used to differentiate original formation water from injected water for waterflood surveillance. Strontium isotopes thus provide a valuable tool for both static and dynamic reservoir characterization in conjunction with conventional studies using seismic, log, core, engineering, and production data.

INTRODUCTION

The strontium isotope composition of formation waters provides a natural tracer for subsurface fluid studies. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of a water sample collected at the wellhead is representative of the subsurface fluid, despite production-induced changes in temperature,

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pressure, or phase that can impact the elemental and/or the stable isotope composition. Numerous studies have applied strontium isotopes to evaluate regional fluid flow and interpret the evolution of fresh and saline groundwaters (e.g., Sunwall and Pushkar, 1979; Starinsky et al., 1983; Stueber et al., 1984, 1987; Posey et al., 1985; Chaudhuri et al., 1987; McNutt et al., 1987, 1990; Notsu et al., 1988; Smalley et al., 1988; Banner et al., 1989; Nakano et al., 1989; Connolly et al., 1990; Chaudhuri and Clauer, 1993; Oetting et al., 1996).

For the Permian basin of southeast New Mexico and west Texas, Stueber et al. (1998) present the most comprehensive published data set of formation water analyses that include Sr isotopes. The focus of their study (and previous investigations by Dutton, 1989; Bein and Dutton, 1993) was to constrain the origin of the formation waters and to interpret regional-scale hydrogeochemical processes. Small-scale compositional heterogeneities among different wells producing from the same field were attributed to variable mixing of meteoric water with connate evaporative brines (Stueber et al., 1998). The spatial distribution of geochemical and isotopic data was not evaluated to determine whether compositional trends exist that may define reservoir regions that are more isolated from meteoric water incursion and other regions that have been more thoroughly invaded by meteoric water. Consequently, the use of Sr isotopes and formation water compositional data to evaluate finer scale subsurface fluid-flow issues, such as reservoir compartmentalization, hydraulic connectivity, and intrareservoir fluid-flow regimes, has not been adequately investigated.

Chaudhuri (1978), finding similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from three wells producing from the same reservoir, first proposed that strontium isotopes could be used to assess hydraulic continuity. Subsequent studies using Sr isotopes have focused on identifying permeability barriers between vertically stacked reservoirs. Russell et al. (1988) reported distinctive $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in waters produced from different formations, implying that the formations are hydraulically segregated. Permeability barriers between vertically stacked compartments in North Sea reservoirs were interpreted from vertical trends in the $^{87}\text{Sr}/^{86}\text{Sr}$ composition of salts leached from core (Smalley et al., 1992; Smalley and England, 1994; Bigno et al., 1997).

In contrast, the variability of formation water $^{87}\text{Sr}/^{86}\text{Sr}$ compositions among multiple wells producing from the same reservoir has not been previously characterized. Reservoirs with relatively uniform formation water $^{87}\text{Sr}/^{86}\text{Sr}$ compositions are likely to be well mixed and homogeneous; abrupt discontinuities in the $^{87}\text{Sr}/^{86}\text{Sr}$ compositions indicate reservoir compartments; and gradual transitions in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios reflect subsurface fluid flow or displacement, dispersion, and mixing of different fluids. Consequently, the strontium isotopic composition of formation waters may be useful to predict reservoir behavior, especially in immature fields where pressure and production data are scarce and the impact of static reservoir properties (e.g., reservoir quality and structure) on reservoir performance is poorly understood. In mature fields, Sr isotopes can serve as a tracer to monitor wastewater injection and

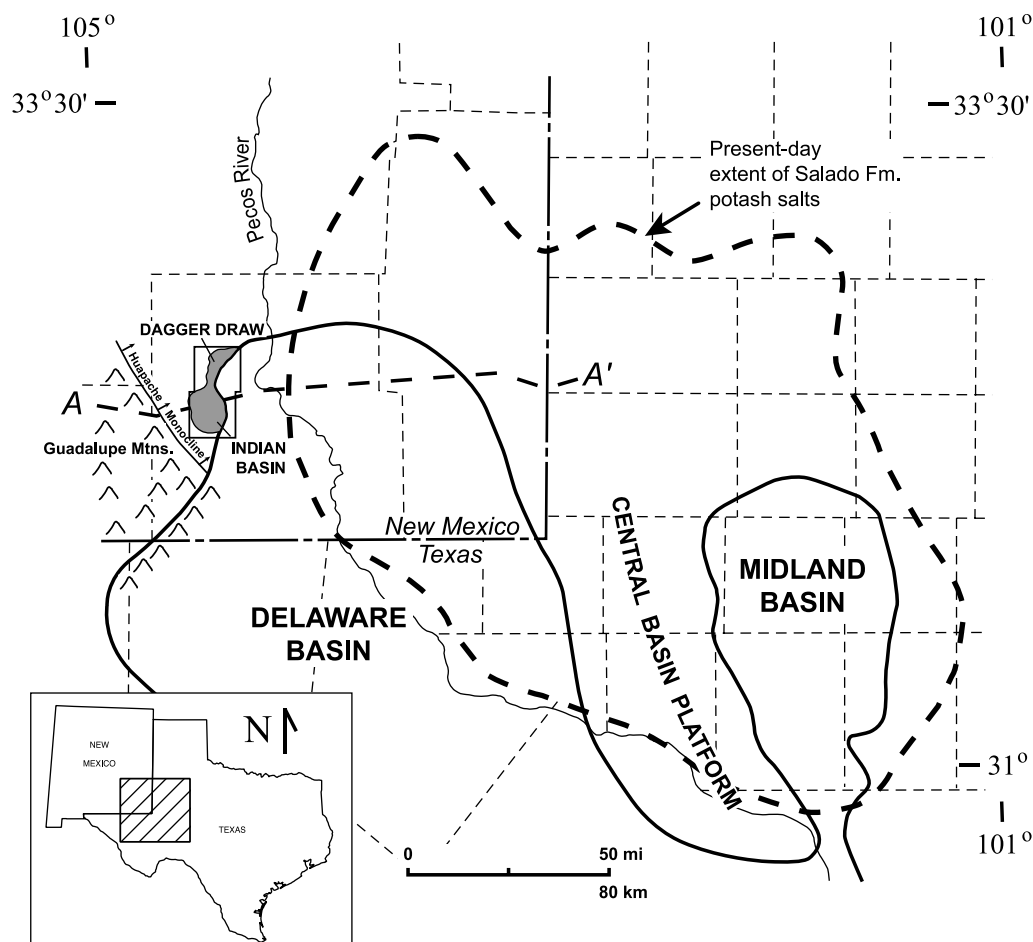


Figure 1. Physiogeographic map of south-eastern New Mexico and west Texas. Indian Basin and Dagger Draw field complex lies east of the Guadalupe Mountains, on the eastward-dipping Huapache monocline. Rectangular trace around the field corresponds to township and range outline for Figure 3. The area of the Salado Formation potassium-bearing evaporite minerals are from Lowenstein (1988). These evaporite deposits formerly extended west to the Guadalupe Mountains but have been eroded to the Pecos River Valley axis by dissolution. Line AA' refers to line of regional cross section in Figure 15.

waterflood recovery, if the injected water has a different Sr content and $^{87}\text{Sr}/^{86}\text{Sr}$ ratio than the in-situ formation water (Smalley et al., 1988), because mixing relationships for two-component systems are well defined (Faure, 1977). Strontium isotopes thus provide a potential tracer for both static (fluid flow on geological timescale) and dynamic (fluid flow on production timescale) reservoir characterization in conjunction with conventional studies using seismic, log, core, well test, and production data.

The major objective of this study was to characterize the spatial distribution of formation water $^{87}\text{Sr}/^{86}\text{Sr}$ compositions to assess the potential use of strontium isotopes as a tracer to evaluate hydraulic connectivity, intrareservoir fluid flow, and reservoir heterogeneity. This report presents data for the elemental, stable isotope, and strontium isotope composition of formation waters collected from 71 wells producing from an active oil and gas field in southeastern New Mexico. Another goal was to use the geochemical and isotopic data to constrain the origin and

chemical evolution of the formation waters and to interpret fluid-flow regimes in the context of the regional Permian basin aquifer system.

The Indian Basin and Dagger Draw fields of southeastern New Mexico (Figure 1), produce oil and gas from upper Pennsylvanian platform margin carbonates. This 125-mi² (325-km²) area was targeted for investigation because of the large volumes of produced water and because the reservoirs are still on primary recovery and are not contaminated by injected water. The gas reservoir in Indian Basin was discovered in 1963 (Frenzel and Sharp, 1975) and has produced more than 1.2 tcf of gas and 7.5 million bbl of condensate (Frenzel, 1988; Speer, 1993; Mazzullo, 1998). Oil and gas reservoirs in Dagger Draw North and Dagger Draw South were discovered in 1964 and 1971 (Broadhead, 1999a). Because of the large volumes of produced water and the low porosity (<7%) determined from conventional porosity logs (Speer, 1993), Dagger Draw remained underdeveloped until the late 1980s and 1990s (Broadhead, 1999a, b). Dagger Draw

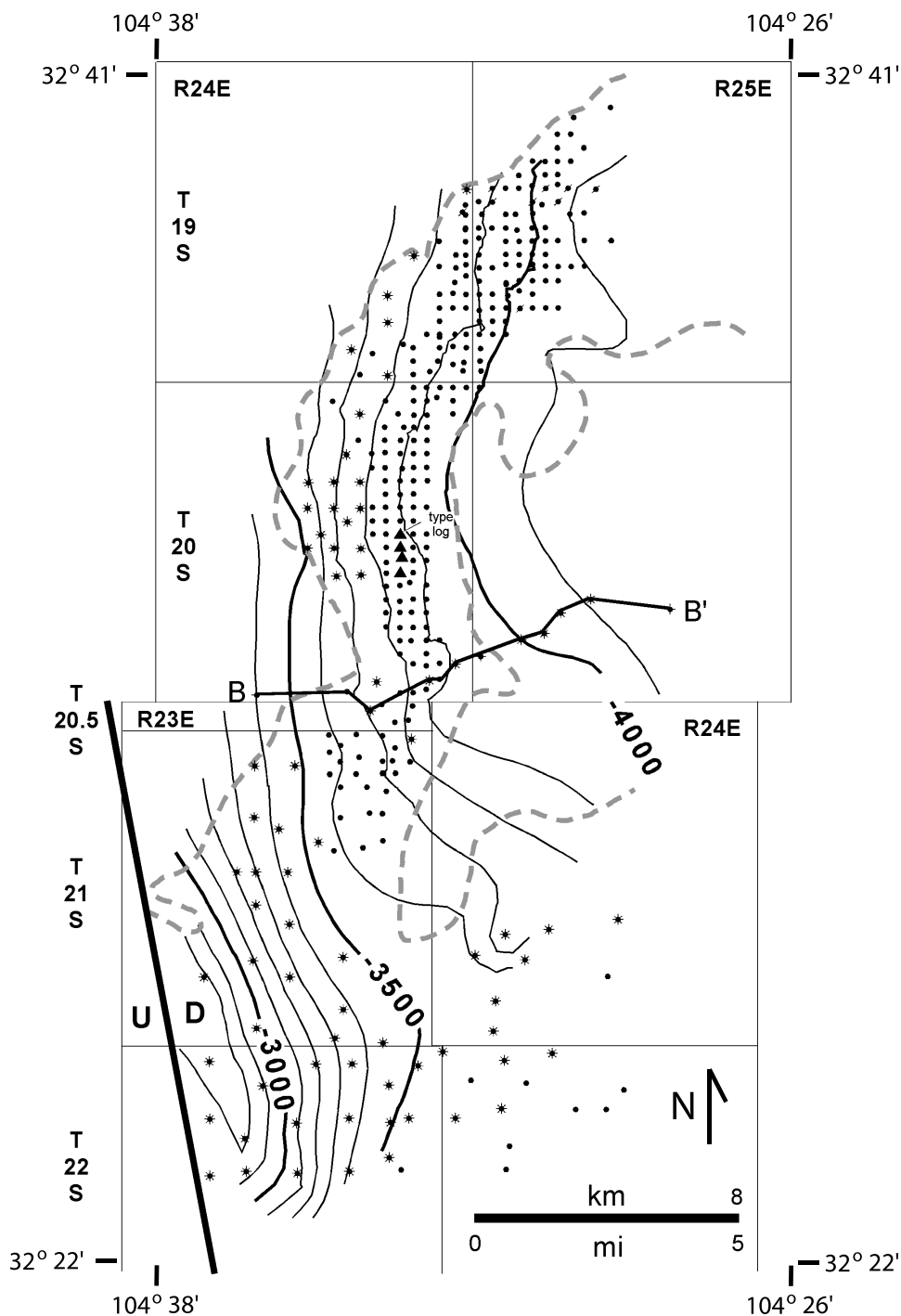


Figure 3. Structural map of top of Cisco (top Pennsylvanian carbonate) for Indian Basin and Dagger Draw field complex. Township and range outline shown in Figure 1. Subsea depth in feet, contour interval 100 ft (30 m). Field limit (dashed) is the extent of the dolomitized shelf margin facies from Yates Petroleum Company (unpublished data, 1994) and Frenzel (1988). Fault location from Marathon Oil Company (unpublished data, 1994). Asterisks are gas wells, dots are oil wells, and triangles are pilot injector wells at time of study.

into lime mud-rich, restricted platform facies and pass basinward and are interbedded with shales and shaly lime mudstones (Cox et al., 1998). The reservoir trap is primarily formed by facies changes from porous shelf margin facies to structurally updip tight lime mud-rich interior platform facies.

Core studies indicate that sequences are composed of multiple depositional cycles defined by 5–30-ft

(1.5–10-m)-thick, upward-shoaling facies successions (Figure 5). Cycle bases consist of argillaceous mudstone to skeletal wackestone, which shoal upward into crinoidal and fusulinid packstone facies, and are capped by algal boundstone and high-energy skeletal grainstone. Because cycle bases commonly are argillaceous rich, major cycles can be identified and correlated using gamma-ray logs (Cox et al., 1998; this study).

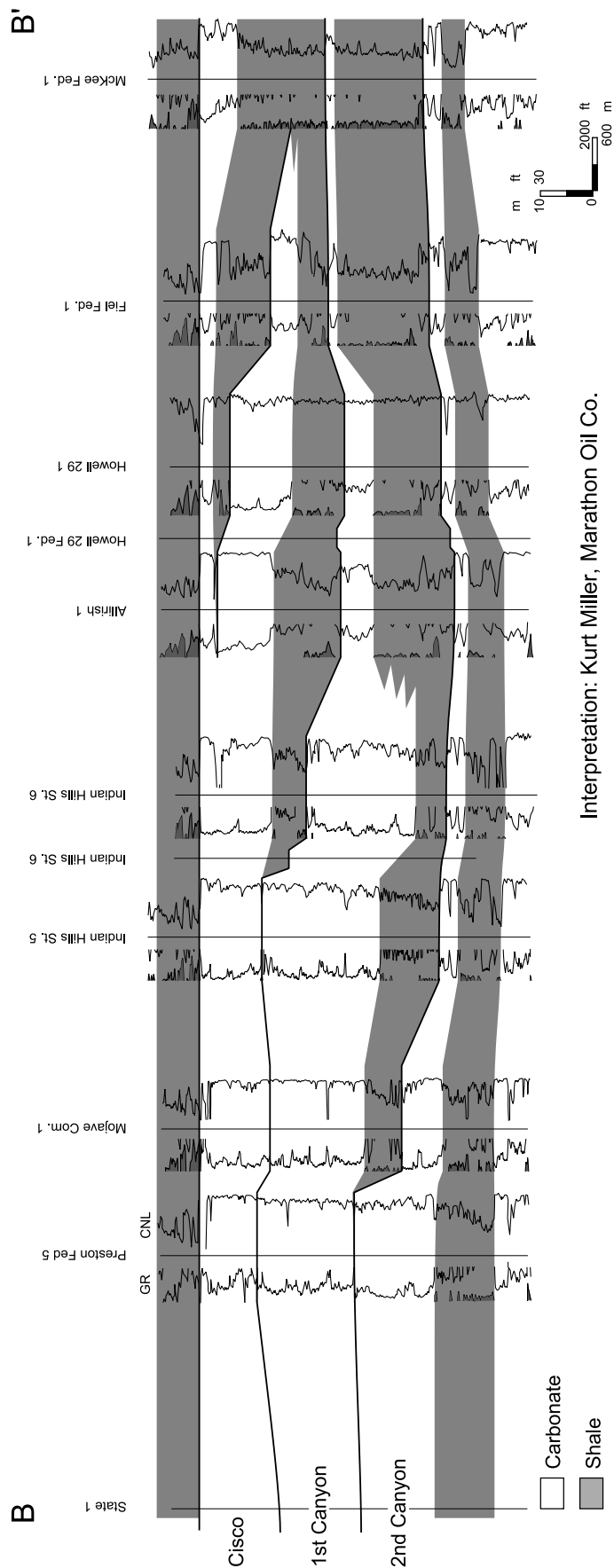


Figure 4. Dip-oriented stratigraphic cross section, datum on top Cisco, location shown in Figure 3. Producing carbonate reservoirs are in three progradational sequences, in ascending stratigraphic order, informally termed the 2nd Canyon, 1st Canyon, and Cisco (Cox et al., 1998). Each carbonate sequence grades basinward into shale and is overlain by transgressive shale that thins onto the platform.

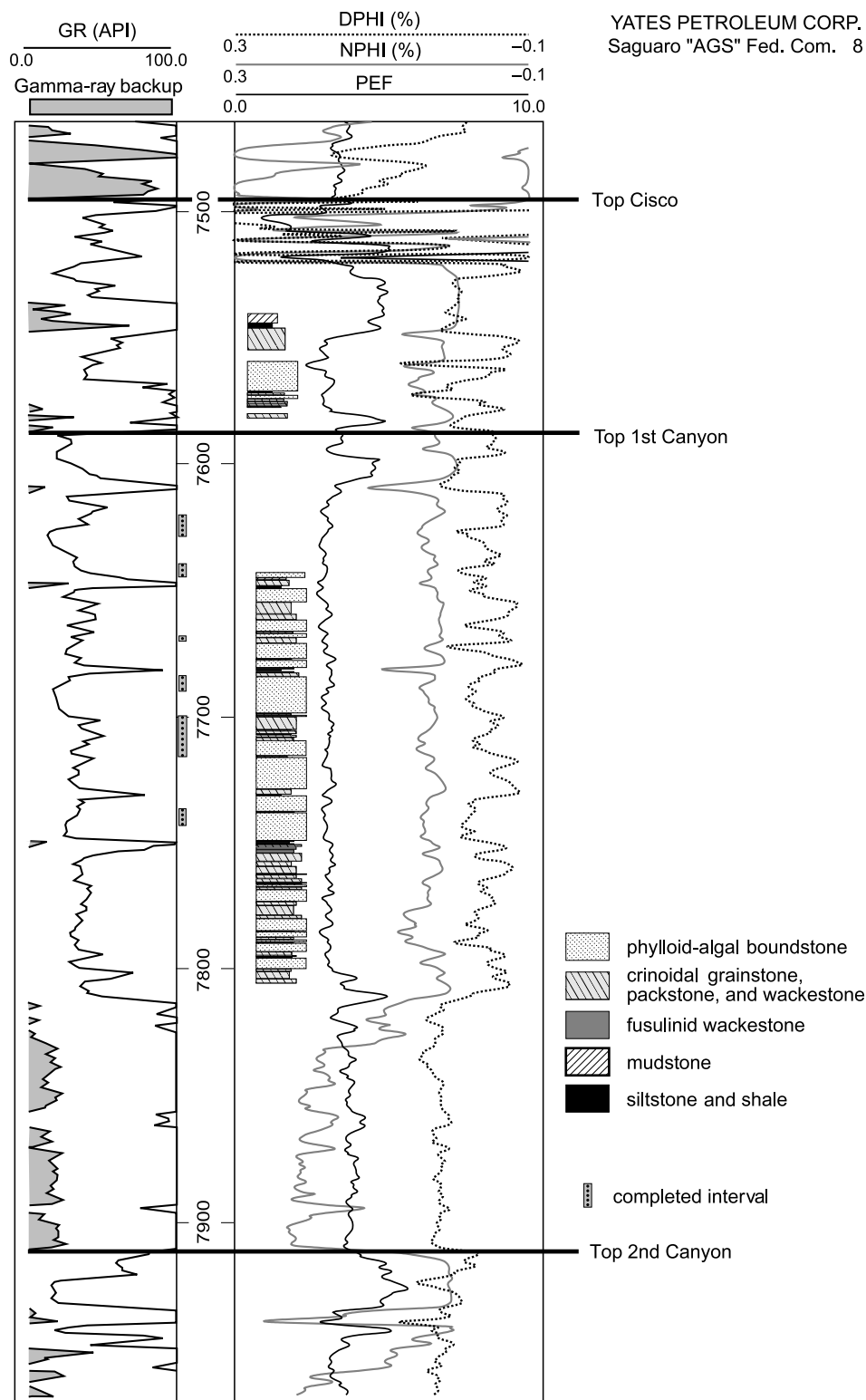


Figure 5. Typical styles of facies stacking and wire-line-log response in upper Pennsylvanian reservoir section, Saguaro "AGS" Fed. Com. 8 (see Figure 3 for well location).

Although depositional facies exert the primary control on porosity and permeability in Indian Basin and Dagger Draw fields, hydrocarbon production is confined to the dolomitized shelf margin, where late

dolomitization and associated dissolution and fracturing generated the intercrystalline and vuggy porosity and high permeability essential for reservoir development (Cox et al., 1998; this study). Although

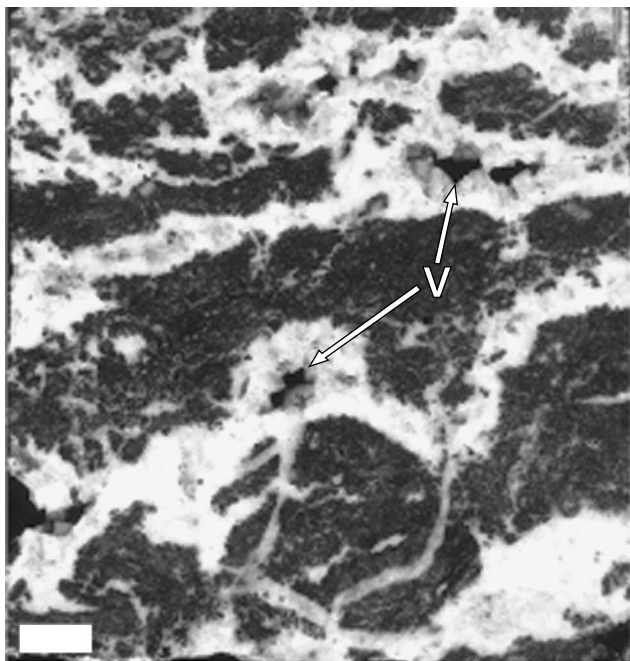
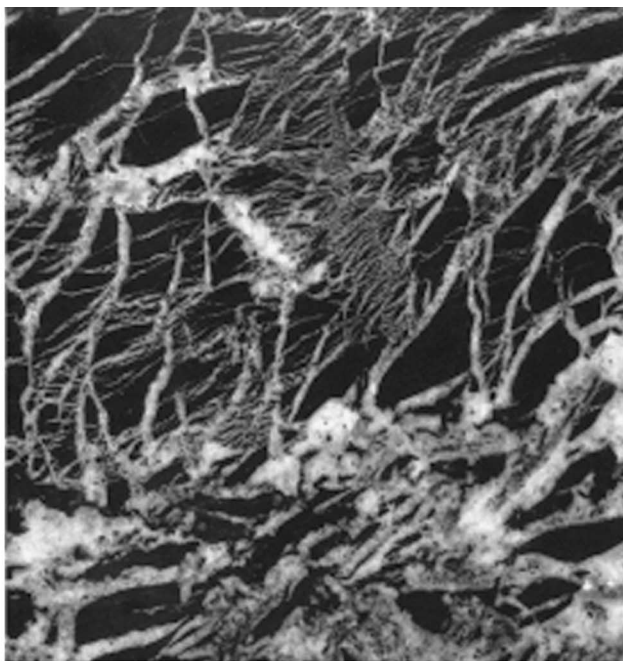
a**b**

Figure 6. Core slab photographs, scale bar = 1 cm (0.4 in.) for both; (a) host dolomite (dark gray), vuggy porosity (v) lined by saddle dolomite cement, (b) host dolomite (dark gray) fractured, followed by saddle dolomite cement.

conventional log porosity is low ($<7\%$), high well production rates are associated with wells completed in zones with vuggy porosity (Speer, 1993; Hurley et al., 1998). Vuggy dissolution and fracturing (Figure 6) was followed by precipitation of saddle dolomite cement and subsequent anhydrite.

Hydrocarbon trapping is influenced by the strong, eastward-directed hydrodynamic drive (Frenzel and Sharp, 1975; Frenzel, 1988; Speer, 1993). Water influx is attributed to the Huapache fault and Huapache monocline (Speer, 1993). The potentiometric gradient determined from drillstem tests indicates that the formation water flows from west to east (Frenzel and Sharp, 1975). This dynamic water drive tilted and displaced the gas-oil-water contacts downdip to the east and northeast; consequently, the updip western and southern portions of the field produce gas and water, whereas the downdip regions produce oil and water (Frenzel and Sharp, 1975; Frenzel, 1988; Speer, 1993).

METHODS

The chemical and isotopic data are from formation water samples collected from 71 wells in the Indian Basin and Dagger Draw fields of Eddy County, New

Mexico between July 1994 and August 1996 (Table 1). To minimize contamination from drilling or completion fluids, samples were collected from oil and gas wells that had been actively producing for at least the past 6 months. Wells with recent workovers or chemical treatment were not sampled. During the first two sample trips, none of the reservoirs had been subjected to waterflooding or wastewater injection. A limited pilot waterflood program was initiated in part of the field in 1995. The injection waters and the produced waters from the offset wells were sampled during early waterflood, but no impact was detected on either the composition of the produced fluids or the production history at the time.

Samples were collected at the oil or gas wellhead, except for several gas wells that were sampled at the separator. Raw production fluids were collected in a collapsible 1-gal (3.8-L) LDPE container and allowed to rest for a few minutes to achieve gravity separation of water and hydrocarbons. Gravity-separated formation water was drained from the LDPE container into a glass wool-packed funnel for raw water and stable isotope aliquot collection. A 40-mL aliquot treated with 3 mL of 5% cadmium acetate solution was collected for analysis of dissolved inorganic carbon. The subsamples for anion, cation, and Sr isotopes were

filtered with acid-cleaned, 0.45- μm polypropylene membrane filters. A 250-mL aliquot was collected for anion analysis, a 120-mL aliquot for cation analysis was acidified with 500 μL of 6N reagent-grade HNO_3 , and a 60-mL aliquot for Sr isotope analysis was acidified with 60 μL of concentrated Seastar ultrapure HNO_3 .

The elemental concentrations in the water samples were analyzed at the Mineral Studies Laboratory of the Bureau of Economic Geology, University of Texas at Austin and by Quanterra Inc. Environmental Services in Austin, Texas. Cations (Na, Ca, K, Mg, and Sr) were analyzed using inductively coupled plasma-atomic emission spectrometry. Cl and Br were determined by ion chromatography, SO_4 was determined by turbidimetric spectrophotometry, and dissolved inorganic carbon was determined using the coulometric carbon analyzer. Of the 76 total samples, the majority (74 samples) have a charge imbalance of less than +0.07. Two samples have a charge imbalance of +0.10. The excess positive charge reflects problems in determining bicarbonate and sulfide (degassing and reequilibration of the samples to the atmosphere), the assumption that all dissolved inorganic carbon occurs as HCO_3^- instead of CO_3^{2-} , and the probable presence of organic acid anions.

Oxygen and hydrogen isotopic measurements of water samples were conducted at the Division of Marine Geology and Geophysics at the University of Miami under the direction of P. K. Swart. These data are reported in conventional notation (‰) relative to Vienna standard marine ocean water (V-SMOW). Replicate analyses of an internal laboratory standard yield a precision of ± 0.08 ‰ for $\delta^{18}\text{O}$ and ± 1.5 ‰ for δD . Analytical methods are reported by Swart and Price (2002). Oxygen and carbon isotope measurements of calcite and dolomite samples were determined at the same laboratory and are expressed relative to the Peedee belemnite. The precision calculated from replicate analysis of an internal laboratory standard is ± 0.03 ‰ for $\delta^{18}\text{O}$ and ± 0.02 ‰ for $\delta^{13}\text{C}$. Analytical methods for the carbonate stable isotope samples are outlined by Leder et al. (1996) and Swart et al. (1996).

The procedure for $^{87}\text{Sr}/^{86}\text{Sr}$ analyses follows that of Oetting (1995). Analyses of National Bureau of Standards (NBS) SRM 987 ($n = 22$) during all sample runs yielded average values ranging from 0.710226 to 0.710260 and $2\sigma_{\text{mean}}$ ranging from ± 0.000008 to ± 0.000012 . The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have been normalized to $^{86}\text{Sr}/^{88}\text{Sr}$ of 0.1194 using an exponential fractionation law and have been adjusted to a value of 0.710255 for NBS SRM 987.

Four sample duplicates yielded $2\sigma_{\text{mean}}$ of ± 0.000013 . Total procedural strontium blanks were less than 2.1 $\mu\text{g/L}$.

Mineral saturation with common evaporite minerals (gypsum, anhydrite, celestite, halite, and sylvite) was computed using SOLMINEQ.88 (Kharaka et al., 1988). For each well, the formation temperature was extrapolated from measured bottomhole temperatures.

RESULTS

Isotopic Composition of Host Rocks

The isotopic data for limestone, replacement dolomite, dolomite cement, and anhydrite cement are presented in Table 2. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ composition of the limestones (Figure 7) are consistent with late Pennsylvanian marine values (Popp et al., 1986a; Lohmann and Walker, 1989). Replacement dolomite and dolomite cement consist of saddle dolomite, which reflects elevated diagenetic temperatures (Gregg and Sibley, 1984). The replacement dolomites display similar $\delta^{13}\text{C}$ compositions to the limestone but are depleted in $\delta^{18}\text{O}$, compatible with late burial replacement at elevated temperatures. The dolomite cements are shifted approximately 1‰ to more depleted $\delta^{18}\text{O}$ values perhaps because of a further increase in temperature; marine carbon continued to buffer the $\delta^{13}\text{C}$ composition.

Expected $^{87}\text{Sr}/^{86}\text{Sr}$ values for late Pennsylvanian seawater (Burke et al., 1982; Popp et al., 1986b; Denison et al., 1994) are 0.7082–0.7083, which coincide with the $^{87}\text{Sr}/^{86}\text{Sr}$ composition of the marine lime mudstones (Figure 8). Although the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the replacement dolomite, dolomite cement, and anhydrite display some variation, they cluster around marine $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, indicating that the strontium isotopic composition of the diagenetic waters was buffered by the host carbonate. The present-day formation waters have high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios relative to the limestone, dolomite, and anhydrite, indicating that they are not in equilibrium with the host rock.

Formation Water Salinity

Formation waters from Indian Basin and Dagger Draw fields (Table 3) contain 2800 to nearly 50,000 mg/L total dissolved solids and are classified as brackish to saline waters (e.g., Davis and DeWiest, 1966). (One gas well, well 8, yielded an anomalously low salinity of 666 mg/L; perhaps the water sample had condensed from a vapor phase as the gas was released into the

Table 1. Formation Water Sample Wells

Well No.	Well Name	Sample Date	Perforated Interval (ft)
1	Chevron Bogle Flats Unit 4	July 1994	7142–7306
2	Chevron Bogle Flats Unit 6	July 1994	7064–7226
3	Chevron Bogle Flats Unit 9	July 1994	7071–7196
4	Conoco Barbara "17-SW" Com. 17	July 1994	7710–7832
5	Conoco Dagger Draw 11	July 1994	7636–7795
6	Conoco Dee State 5	July 1994	7734–7856
7	Marathon Federal IBB Gas Com. 1 (314)	July 1994	7486–7564
8	Marathon Federal IBC Gas Com. 1 (229)	July 1994	6958–7055
9	Marathon Indian Hills Unit Gas Com. 3 (129)	July 1994	7262–7322
10	Yates Hillview "AHE" Federal Com. 12	July 1994	7588–7743
11	Yates LaRue XX Federal 1	July 1994	7679–7736
12	Yates Patriot "AIZ" Com. 2	July 1994	7645–7754
13	Yates State "CO" Com. 7	July 1994	7710–7826
14	Yates Molly "QD" Com. 2	July 1994	7717–7874
15	Yates Ross "EG" Federal 12	July 1994	7792–7840
16	Yates Roy "AET" 4	July 1994	7752–7814
17	Yates Algerita "AHR" State 1	July 1994	7438–7572
18	Yates Mojave "AJY" Com. 1	July 1994	7444–7450
19	Conoco Preston Federal Well 5	December 1994	7715–7782
20	Conoco Jenny Com. 2	December 1994	7765–7862
21	Marathon Indian Basin "A" 2	December 1994	7312–7400
22	Marathon Indian Hills State Com. 1	December 1994	7564–7603
23	Marathon Indian Hills State Com. 3	December 1994	7714–7740
24	Marathon Federal 1	December 1994	7560–7627
25	Marathon Federal 4	December 1994	7640–7752
26	Marathon North Indian Basin Unit 8	December 1994	7400–7416; 9167–9185
27	Yates Hooper "AMP" 1	December 1994	7710–7817
28	Yates Hooper "AMP" 2	December 1994	7678–7800
29	Yates Candelilla "AKD" State Com. 1	February 1996	7738–7816
30	Yates Candelilla "AKD" State Com. 2	February 1996	7728–7818
31	Yates Carl "TP" Com. 2	February 1996	7549–7600
32	Yates Carl "TP" Com. 3	February 1996	7606–7690
33	Yates Carl "TP" Com. 4	February 1996	7618–7714
34	Conoco "AGK" Federal 6	February 1996	7687–7764
35	Conoco "AGK" Federal 7	February 1996	7703–7766
36	Conoco "AGK" Federal 8	February 1996	7690–7740
37	Yates Dahlia "ALA" Com. 1	February 1996	7653–7724
38	Yates Foster "AN" 1	February 1996	7754–7820
39	Yates Foster "AN" 3	February 1996	7714–7792
40	Yates Hillview "AHE" Federal Com. 11	February 1996	7658–7770
41	Yates Ocotillo "ACI" Federal 2	February 1996	7621–7744
42	Yates Palo Verde "AJV" Federal Com 1	February 1996	7718–7780
43	Yates Saguario "AGS" Federal Com. 4	February 1996	7660–7774
44	Yates Saguario "AGS" Federal 10	February 1996	7650–7730
45	Yates Saguario "AGS" Federal Com. 12	February 1996	7718–7752
46	Yates Sara "AHA" 2	February 1996	7616–7729

Table 1. Continued

Well No.	Well Name	Sample Date	Perforated Interval (ft)
47	Yates Sara "AHA" Com 8	February 1996	7750–7804
48	Yates Hillview "AHE" Federal Com. 5	August 1996	7598–7798
49	Yates Hillview "AHE" Federal 8	August 1996	7594–7752
50	Yates Hillview "AHE" Federal 10	August 1996	7628–7779
51	Yates Hillview "AHE" Federal Com. 13	August 1996	7677–7806
52	Yates Saguaro "AGS" Federal Com. 5	August 1996	7626–7744
53	Yates Saguaro "AGS" 9	August 1996	7617–7760
54	Yates Senita 2	August 1996	7680–7777
55	Marathon Bone Flats "12" 1	August 1996	7740–7808
56	Marathon Bone Flats "12" 3	August 1996	7778–7868
57	Marathon Federal 2	August 1996	7790–7860
58	Marathon Federal 6	August 1996	7744–7808
59	Marathon Federal 8	August 1996	7740–7830
60	Marathon North Indian Basin Unit 12	August 1996	7640–7806
61	Marathon North Indian Basin Unit 16	August 1996	7772–7858
62	Marathon North Indian Basin Unit 18	August 1996	7652–7808
63	Marathon North Indian Basin Unit 20	August 1996	7674–7786
64	Marathon North Indian Basin Unit 23	August 1996	7672–7828
65	Marathon North Indian Basin Unit 26	August 1996	7710–7780
66	Marathon Stinking Draw 2	August 1996	7653–7769
67	Marathon Stinking Draw 3	August 1996	7668–7715
68	Yates Anemone "ANE" Federal 3	August 1996	8106–8156
69	Yates Atom "ANT" Federal Com 1	August 1996	7978–8002
70	Yates Brannigan "ANF" Federal 2	August 1996	8017–8050
71	Yates Pan Am Pardue "ALZ" Federal Com 1	August 1996	7999–8071
72	Injection waters for Yates Saguaro 8, and Yates Hillview 2, 4, and 6	August 1996	

atmosphere during sampling. Data from this well are not included in Figures 9–14.) The formation waters are Na-Cl-SO₄-type waters (e.g., Kharaka et al., 1985), NaCl accounts for 40–90% of the total dissolved solids (Figure 9a), and the Na/Cl molar ratio approaches 1:1 at higher salinities (Figure 9b). Although the waters are undersaturated with respect to halite, there is a well-defined relationship between the NaCl saturation index and the Na⁺ concentration (Figure 10a), suggesting that the Na⁺ content is governed by halite dissolution. A similar relationship exists between the KCl saturation index and the K⁺ concentration, suggesting that the K⁺ content is governed by the dissolution of sylvite or other potassium-rich evaporite minerals. Most of the formation waters are near saturation with respect to anhydrite and gypsum, which constitute the primary source for Ca²⁺ and SO₄²⁻.

Formation Water Br and Cl

The bromine content (Rittenhouse, 1967) and Br/Cl ratios of formation waters (e.g., Carpenter et al., 1974; Carpenter, 1978; Banner et al., 1989) can be used to distinguish between saline waters derived from seawater (i.e., seawater, evaporated seawater or seawater diluted by meteoric water) and saline waters derived from halite dissolution. Because bromine is a conservative element during seawater evaporation and is not readily incorporated into halite, formation waters with depleted Br/Cl ratios record halite dissolution (Carpenter, 1978). The low Br/Cl ratios for most of the formation waters in the Indian Basin and Dagger Draw reservoir complex (Figure 10b), imply that the salinities were acquired by halite dissolution. The variable Br/Cl ratios do not exhibit a clear mixing trend and

Table 2. Isotopic Analyses for Reservoir Host Rocks

Well Name	Depth (ft)	Lithology	$\delta^{13}\text{C}$ (PDB)	$\delta^{18}\text{O}$ (PDB)	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ
Conoco Barbara Federal 12	7700.3	lime mudstone	2.31	−3.80	0.708338	±9
Conoco Barbara Federal 12	7904.5	lime mudstone	4.09	−4.06	0.708384	±9
Marathon N. Indian Basin Unit 1	7409.0	lime mudstone	1.42	−3.25	0.708288	±9
Marathon N. Indian Basin Unit 1	7662.4	lime mudstone	2.84	−4.14	0.708331	±10
Yates Saguaro 8	7552.7	lime mudstone	0.88	−3.04	0.708279	±9
Yates Saguaro 8	7813.0	lime mudstone	4.11	−4.12	0.708283	±10
Conoco Barbara Federal 12	7766.9	replacement dolomite	0.60	−5.57	0.708640	±10
Conoco Barbara Federal 12	7856.5	replacement dolomite	4.00	−6.28	0.708234	±12
Marathon Indian Hill 6	7758.8	replacement dolomite	2.73	−5.37	0.708228	±10
Marathon N. Indian Basin Unit 1	7378.7	replacement dolomite	0.78	−5.28	0.708054	±9
Marathon N. Indian Basin Unit 1	7492.5	replacement dolomite	0.37	−6.70	0.708108	±10
Yates Saguaro 8	7577.0	replacement dolomite	3.20	−5.31	0.708513	±8
Yates Saguaro 8	7764.1	replacement dolomite	2.97	−6.60	0.708120	±9
Conoco Barbara Federal 12	7828.0	saddle dolomite cement	2.29	−6.63	0.708481	±10
Conoco Barbara Federal 12	7874.1	saddle dolomite cement	2.62	−6.27	0.707998	±10
Yates Saguaro 8	7656.9	saddle dolomite cement	2.06	−7.74	0.708944	±10
Yates Saguaro 8	7739.0	saddle dolomite cement	2.58	−6.34	0.708062	±10
Marathon Indian Hill 6	7751.0	anhydrite cement			0.708595	±12
Marathon Indian Hill 6	7776.0	anhydrite cement			0.708550	±9
Marathon N. Indian Basin Unit 1	7465.0	anhydrite cement			0.708409	±9
Marathon N. Indian Basin Unit 1	7527.0	anhydrite cement			0.708206	±8
Yates Saguaro 8	7711.7	anhydrite cement			0.708586	±9
Yates Saguaro 8	7714.0	anhydrite cement			0.708539	±10

may reflect further dilution of the halite-derived solutes by meteoric waters (e.g., Land and Prezbindowski, 1981).

Formation Water Stable Isotopes

The δD and $\delta^{18}\text{O}$ values of the formation waters (Table 3, Figure 11) cluster along the global meteoric water line of Craig (1961). The data are within $\pm 8\text{‰}$ in δD and $\pm 1\text{‰}$ $\delta^{18}\text{O}$ relative to the meteoric water line, within the statistical limits of the line and data. This indicates that the brackish to saline formation waters are of meteoric origin. The δD and $\delta^{18}\text{O}$ compositions coincide with values reported for precipitation, surface water, and shallow groundwater samples in southeastern New Mexico (Hoy and Gross, 1982) and with δD and $\delta^{18}\text{O}$ data for groundwater in deeper confined aquifers of eastern New Mexico and west Texas (Dutton, 1995). Using the oxygen isotope fractionation factors for calcite-water ($10^3\ln \alpha = 2.78 \times (10^6/T^2) - 2.89$) and dolomite-water ($10^3\ln \alpha = 3.20 \times (10^6/T^2) -$

1.50) from Friedman and O'Neil (1977) indicates that the formation waters have not isotopically equilibrated with the host dolomite or calcite at reservoir temperatures (50–60°C).

Formation Water Strontium Isotopes

Late Pennsylvanian seawater $^{87}\text{Sr}/^{86}\text{Sr}$ values are approximately 0.7082–0.7083 (Burke et al., 1982; Popp et al., 1986b; Denison et al., 1994) adjusted to NBS 987 = 0.710255. All of the Indian Basin and Dagger Draw formation water samples are enriched in ^{87}Sr relative to marine values (Table 3; Figure 8), except for one sample, well 1. The low $^{87}\text{Sr}/^{86}\text{Sr}$ from well 1 may reflect flow into the wellbore from overlying Permian strata. This well is one of the oldest gas producers (1965 completion) sampled, and it is possible that the casing has been breached by corrosion. The $^{87}\text{Sr}/^{86}\text{Sr}$ and compositional data from wells 1 and 8 are omitted from further discussion and are not plotted in Figures 9–14.

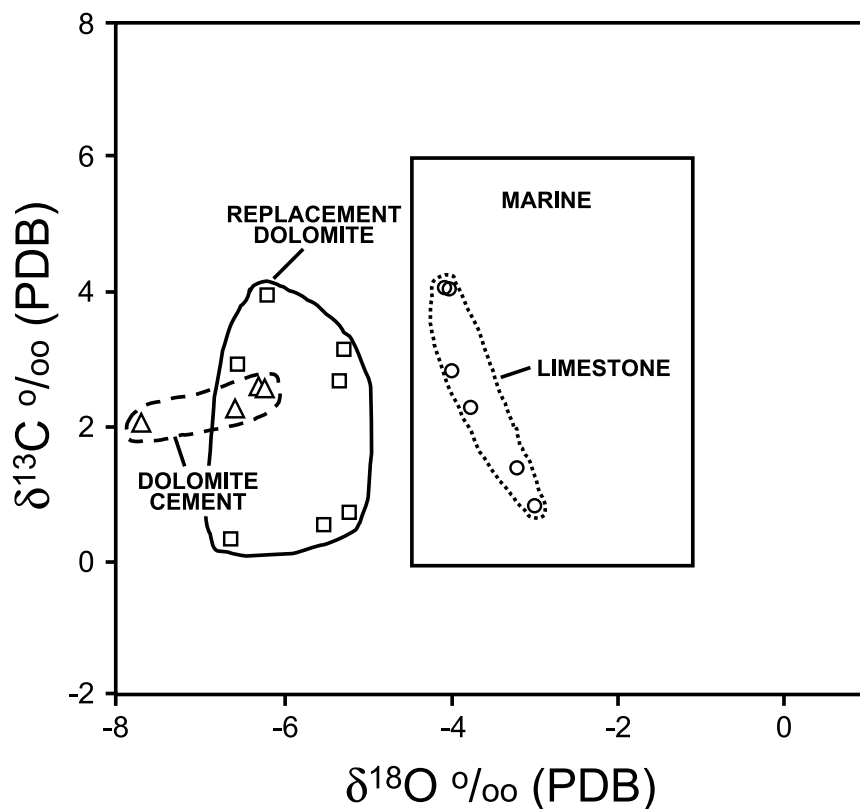


Figure 7. Stable isotope data for carbonate samples. Nondolomitized limestones coincide with expected marine values (Popp et al., 1986a; Lohmann and Walker, 1989); replacement dolomite and dolomite cement are depleted in ^{18}O , consistent with elevated diagenetic temperatures.

For the remaining 69 wells, formation water $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.708903 to 0.710129, and Sr content ranges from 8 to 40 mg/L. Formation waters are enriched in radiogenic ^{87}Sr relative to the

host rocks: marine limestone, replacement dolomite, dolomite cement, and anhydrite cement (Figure 8). The data (Figure 12a) do not define a clear mixing trend between two components with different Sr contents and

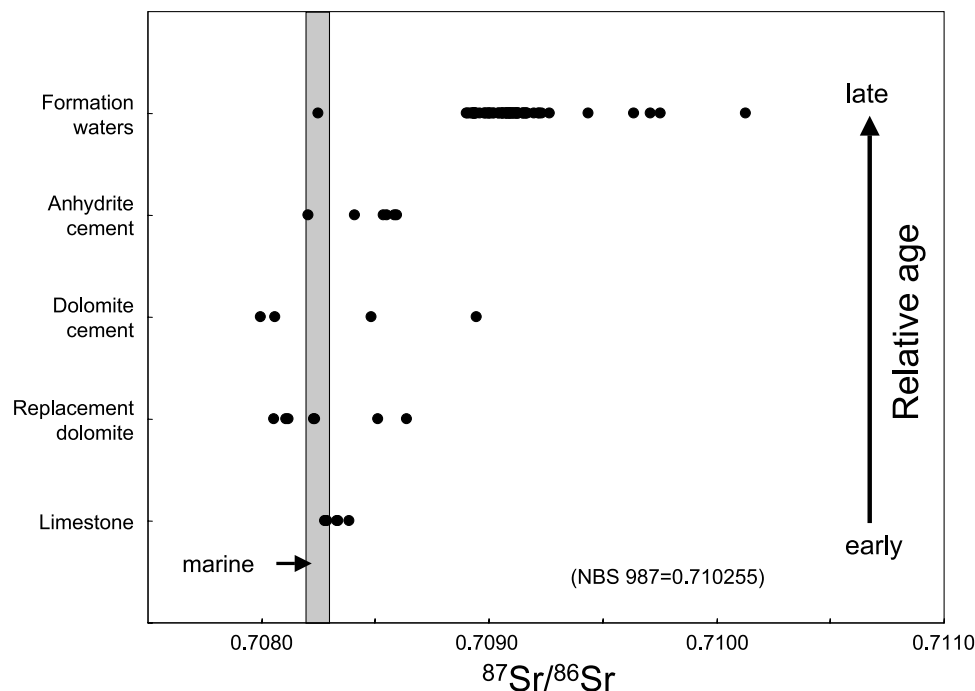


Figure 8. $^{87}\text{Sr}/^{86}\text{Sr}$ composition of rock samples and formation waters from Indian Basin and Dagger Draw field complex, plotted in paragenetic order, with the oldest (limestone) at the bottom and the youngest (present-day formation waters) at the top of the diagram. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of host rocks (limestone, dolomite, and anhydrite) cluster around marine values, whereas formation waters have more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Table 3. Formation Water Chemical and Isotopic Analyses

Well Number	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Sr (mg/L)	Cl (mg/L)	SO ₄ (mg/L)	Br (mg/L)	HCO ₃ (mg/L)	TDS (mg/L)	⁸⁷ Sr/ ⁸⁶ Sr (0.710255)	2σ	δD SMOW	δ ¹⁸ O SMOW
1	27	22	3210	112	2	4090	265	6.9	26	7760	0.708252	±12		
2	1220	525	6480	704	11	9780	1230	15.8	94	20,059	0.710129	±14		
3	1080	164	7700	76	26	11,140	2200	57.6	147	22,590	0.709712	±11		
4	578	129	2090	49	14	1850	2240	1.9	130	7082	0.709105	±08		
5	489	95	2070	44	12	1500	2480	2.0	90	6782	0.709091	±08		
6	500	93	1730	38	12	1280	2280	0.6	157	6091	0.709076	±10		
(duplicate) 6											0.709078	±13		
7	366	125	4860	290	8	6600	79	0.4	23	12,351	0.709438	±11		
8	85	15	99	65	1	316	85	<0.3	<5	666	0.709077	±09		
9	558	104	2440	45	14	2320	2150	4.8	177	7812	0.709108	±12		
10	457	87	1300	34	12	920	1900	2.4	105	4818	0.708998	±09	-55.87	-8.00
11	519	109	1530	39	13	1160	2100	1.3	106	5576	0.709075	±10	-54.46	-8.84
12	434	87	2330	68	11	1600	2580	2.1	25	7137	0.709156	±10		
13	526	104	1570	41	13	1290	2030	2.5	152	5729	0.709089	±10	-56.00	-8.40
(duplicate) 13											0.709092	±10		
14	518	111	1760	48	13	1370	2370	0.7	83	6274	0.709090	±12	-51.16	-7.52
15	559	129	1990	37	13	1990	2370	3.8	<5	7093	0.709120	±09	-54.21	-7.72
16	484	102	4580	68	11	4630	3750	3.6	<5	13,628	0.709083	±10		
17	908	211	4800	489	24	7820	1990	6.6	84	16,333	0.709635	±10		
18	288	96	1220	45	11	860	2030	0.9	ins.	4551	0.708983	±12		
19	840	174	4780	86	23	7113	2330	12.9	157	15,517	0.709755	±10	-48.28	-7.51
20	644	198	2317	30	11	2748	3200	3.8	189	9341	0.709167	±10		
21	1374	186	18,380	175	38	25,690	2770	18.0	351	48,982	0.709097	±10		
22	421	95	1278	118	11	973	1760	<0.5	277	4933	0.709042	±09	-49.10	-8.00
23	464	92	1209	31	12	863	2070	<0.5	254	4995	0.709019	±12		
(duplicate) 23											0.709009	±13		
24	454	97	1164	40	12	809	2050	1.3	260	4887	0.709007	±08	-57.06	-8.23
25	472	98	1082	70	12	822	2050	<0.5	314	4920	0.708939	±11	-55.85	-8.00
26	1132	206	11,280	117	32	16,480	2000	16.7	293	31,557	0.709199	±10		
27	430	78	2310	31	10	1778	2490	<1	158	7285	0.709119	±09		
28	505	106	1924	65	12	1861	2970	<1	242	7685	0.709148	±10	-49.69	-7.28
(duplicate) 28											0.709184	±10		
29	522	104	2430	50	13	1210	2280	6.4	3	6619	0.709235	±09		

30	501	116	1770	42	12	1780	2390	3.3	124	6739	0.709220	±11	-49.24	-8.00
31	497	104	1350	35	14	1390	1910	<0.5	131	5431	0.709101	±10	-53.62	-8.95
32	478	106	1650	46	14	1890	1910	4.1	156	6254	0.709106	±11	-53.30	-7.43
33	495	100	4020	267	13	5560	2040	4.4	1	12,501	0.709001	±08	-54.64	-7.20
34	501	111	1360	37	13	1410	1790	3.2	169	5394	0.709092	±08	-58.61	-7.75
35	457	89	1700	41	12	1710	2040	3.2	129	6183	0.709171	±11	-54.65	-8.02
36	439	82	1050	40	12	795	1610	1.3	142	4172	0.709002	±10		
37	428	81	1170	34	12	895	1740	2.2	232	4593	0.709025	±10	-52.09	-7.37
38	519	110	2120	68	14	2550	2090	6.4	150	7628	0.709118	±11	-51.92	-7.84
39	449	83	1460	38	11	1240	1960	3.3	200	5445	0.709055	±12	-61.22	-8.27
40	501	103	1580	40	14	1680	1630	3.3	162	5713	0.709116	±09	-54.70	-8.40
41	476	106	1580	39	13	1610	1830	3.2	145	5803	0.709133	±09	-55.71	-7.89
42	489	98	1310	95	13	1320	1630	2.6	208	5166	0.709064	±09	-57.00	-8.23
43	524	110	1890	56	14	2360	1960	4.0	119	7037	0.709128	±10	-56.14	-8.40
44	453	86	1390	45	13	1240	1910	2.4	4	5143	0.709060	±11	-57.74	-8.64
45	450	93	1520	36	13	1390	2040	3.5	175	5719	0.709149	±10	-55.36	-7.12
46	474	97	1520	38	13	1520	1830	2.8	146	5641	0.709223	±11	-55.11	-8.62
47	458	89	1340	40	12	1130	2070	2.3	210	5352	0.709064	±11	-53.28	-8.20
48	539	101	1700	51	13	2080	1870	6.7	35	6395	0.709125	±10		
49	543	116	1610	56	13	1770	1920	5.4	25	6058	0.709062	±09		
50	613	96	1810	57	15	2290	2060	7.8	37	6986	0.709092	±09		
51	442	89	1340	27	11	1100	1920	3.6	37	4970	0.709045	±10		
52	361	114	2250	82	11	2550	1680	7.4	11	7066	0.709129	±11		
53	613	122	2060	68	12	2450	1940	7.0	27	7299	0.709161	±11		
54	604	125	2110	65	15	2320	1920	6.7	26	7191	0.709167	±09		
55	447	88	1030	37	17	651	1600	2.4	29	3901	0.708932	±10		
56	464	90	986	30	15	666	1590	2.5	35	3878	0.708934	±10	-55.56	-8.40
57	414	81	1080	29	14	771	1780	2.7	11	4182	0.708937	±09	-54.27	-8.29
58	442	91	1040	31	14	778	1690	2.8	21	4109	0.708933	±09		
59	473	101	1080	31	12	840	1800	2.6	28	4368	0.708928	±12		
60	473	88	976	37	15	720	1610	2.6	15	3937	0.708960	±08		
61	423	85	945	34	15	695	1640	2.5	29	3869	0.708936	±10		
62	450	89	1340	29	14	1230	1700	3.2	13	4868	0.708990	±08		
63	491	91	1190	29	16	1010	1690	2.8	36	4555	0.708946	±11		
64	598	122	2460	47	19	3800	1810	12.1	33	8901	0.709266	±11		
65	514	98	1420	27	18	793	856	5.1	25	3756	0.709078	±10	-57.98	-8.22
66	448	85	1070	29	14	367	840	2.8	29	2884	0.708941	±11	-56.12	-8.47

Table 3. Continued

Well Number	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Sr (mg/L)	Cl (mg/L)	SO ₄ (mg/L)	Br (mg/L)	HCO ₃ (mg/L)	TDS (mg/L)	⁸⁷ Sr/ ⁸⁶ Sr (0.710255)	2σ	δD SMOW	δ ¹⁸ O SMOW
67	431	86	1040	31	12	368	846	2.8	25	2843	0.708982	±10	-56.01	-8.35
68	477	91	1080	34	14	395	866	3.0	29	2989	0.708903	±09		
69	677	209	1110	46	12	798	858	3.2	25	3738	0.708906	±10		
70	463	96	1560	35	13	1910	1730	5.5	20	5832	0.708935	±09		
71	512	103	1280	37	13	1060	1800	3.3	27	4835	0.708916	±11	-55.75	-8.09
72	660	140	2210	132	16	2830	2310	8.3	22	8328	0.709090	±10	-54.47	-8.88

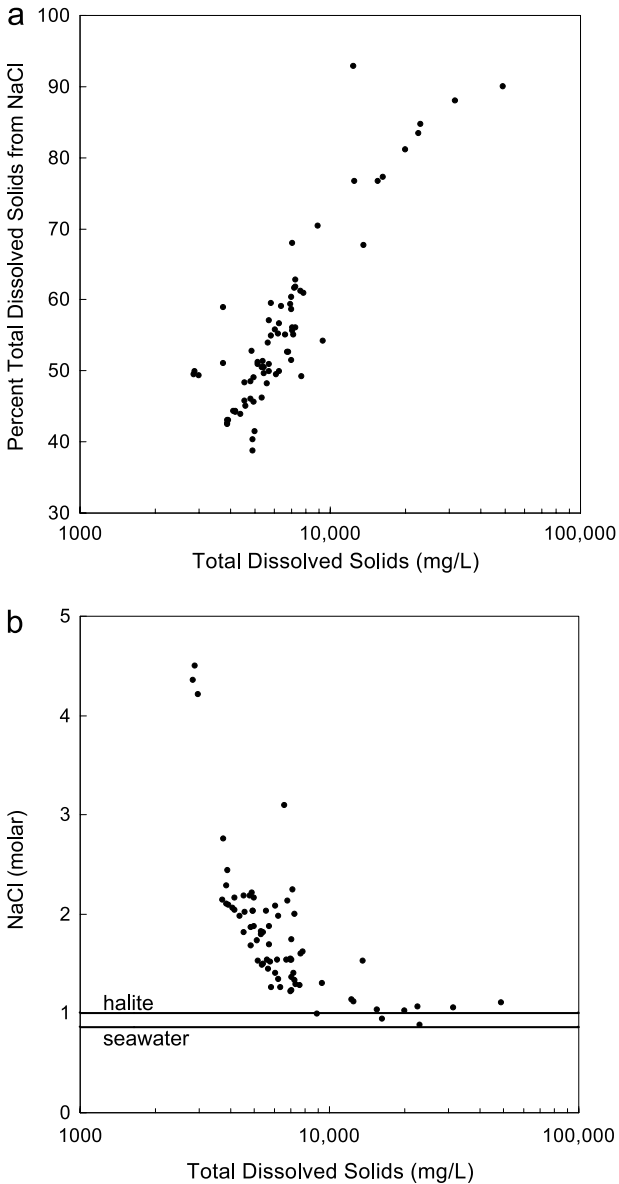


Figure 9. (a) Crossplot of formation water total dissolved solids vs. percent of total dissolved solids contributed by halite dissolution; the most saline waters contain the highest proportion of dissolved NaCl. (b) Crossplot of formation water total dissolved solids vs. Na/Cl molar ratio. As salinity increases, the Na/Cl molar ratio approaches unity, indicating that the high-salinity waters derived most of their solutes from halite dissolution.

⁸⁷Sr/⁸⁶Sr ratios (e.g., Faure, 1977). Nor do the data display a well-defined relationship with depth (Figure 12b), except that the most radiogenic and most highly variable Sr isotopic ratios are from shallower depths, and the least radiogenic waters are from greater depths. No relationship was discerned between the ⁸⁷Sr/⁸⁶Sr

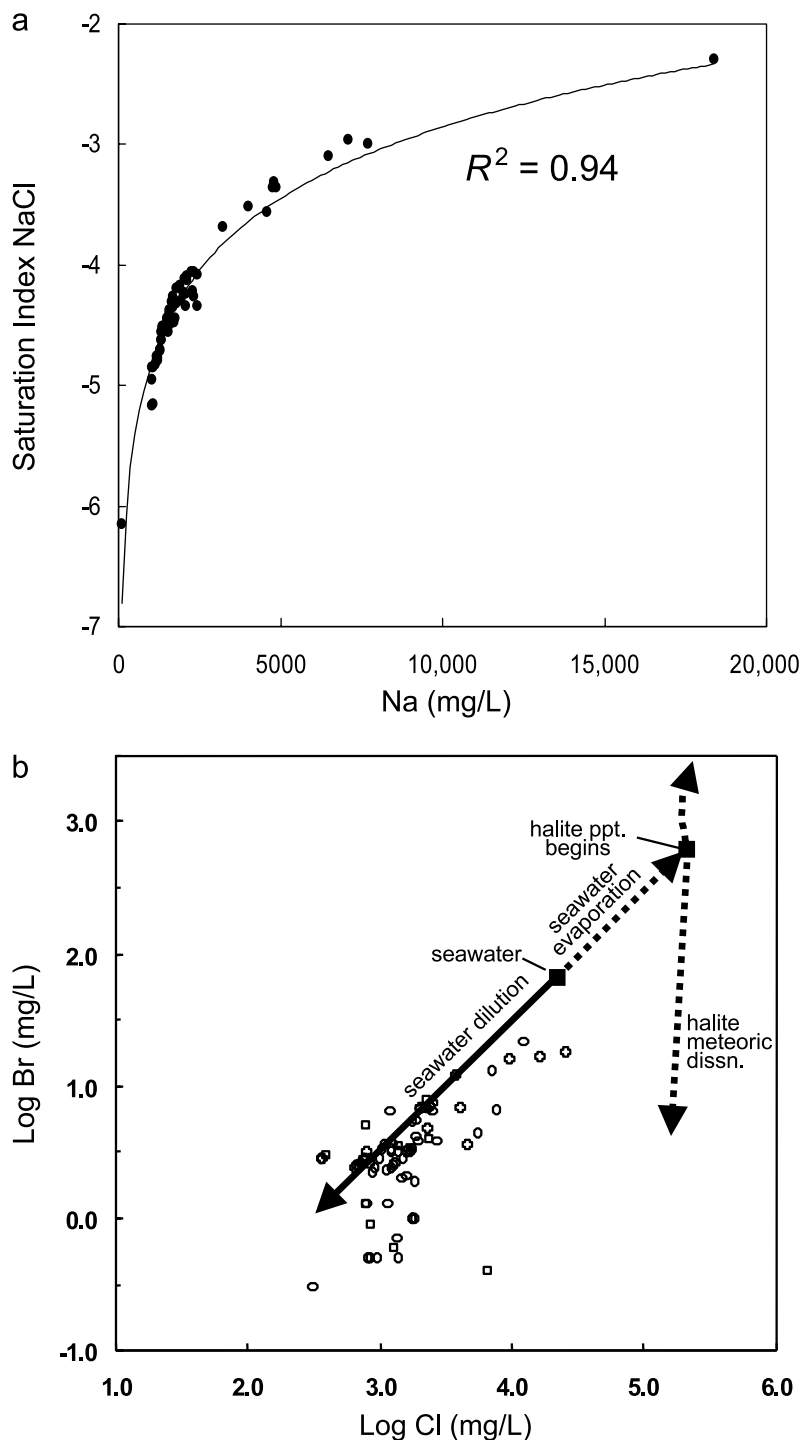


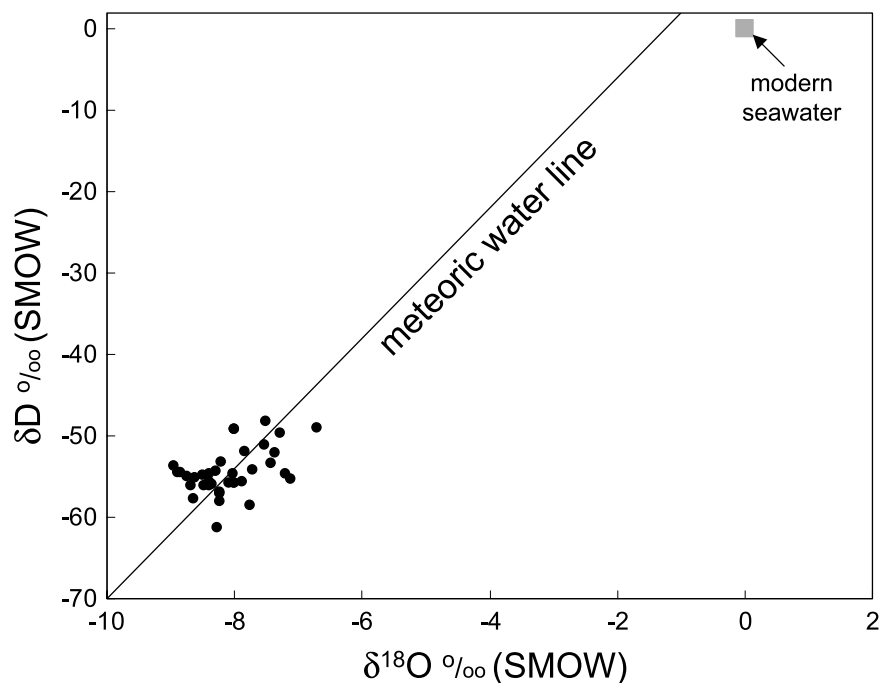
Figure 10. (a) Crossplot of formation water Na concentration vs. NaCl saturation index computed at formation temperature using SOLMINEQ.88. The well-defined relationship indicates that the solute composition is governed by halite dissolution. (b) Crossplot of formation water Br and Cl concentrations. The Br/Cl ratio for seawater evaporation trend to past halite precipitation from Zherebtsova and Volkova (1966), Collins (1969), Herrmann and Knake (1973), and Carpenter (1978). Dilution of seawater by meteoric water or evaporative concentration of seawater to the point of halite precipitation does not change the Br/Cl ratios. Most formation waters in the Indian Basin and Dagger Draw reservoir complex have low Br/Cl ratios, indicating dissolution of halite by meteoric water.

composition of the formation water and the stratigraphic interval from which it was produced.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the formation waters display a well-defined, west-to-east gradient across the field complex (Figure 13). Formation waters in the updip southern and western regions have the most radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ values, which grade downdip to less

radiogenic waters. Five wells were resampled at intervals of 5–25 months to evaluate the consistency of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Table 4). In four of these wells, the difference in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios was insignificant, limited to the fifth or sixth decimal place. In one updip well, Algerita State 1, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio increased somewhat during the 19 months that elapsed between sample trips.

Figure 11. Crossplot of the δD and $\delta^{18}O$ of formation water samples, meteoric water line from Craig (1961). The data cluster around the meteoric water line, indicating that they are derived from meteoric precipitation and have not interacted extensively with ^{18}O -rich carbonate or siliciclastic minerals in the host rocks or in overlying strata.



INTERPRETATION

Origin of Brackish to Saline Formation Waters

The trends defined by the total dissolved solids vs. the percent total dissolved solids contributed by NaCl (Figure 9a), the total dissolved solids vs. the Na/Cl molar ratios (Figure 9b), the NaCl saturation trend (Figure 10a), and the Br/Cl ratios (Figure 10b) confirm that the bulk of the solutes in the formation waters were derived from the dissolution of halite and associated evaporite minerals. The $\delta^{18}O$ compositions are diagnostic of meteoric freshwater (Figure 11) that has not significantly interacted diagenetically with the $\delta^{18}O$ -rich carbonate host rocks or with overlying carbonate and siliciclastic strata. In the Permian basin, bedded halite is confined to Upper Permian (Guadalupian and Ochoan) evaporites. Consequently, the brackish to saline formation waters in Indian Basin and Dagger Draw fields record influx of meteoric waters that acquired their salinity from evaporite dissolution.

The Pennsylvanian strata in the Indian Basin and Dagger Draw reservoir complex comprise the updip limit of the deep-basin aquifer system of Bassett and Bentley (1982) and Bein and Dutton (1993). Tectonic uplift and tilting in eastern New Mexico during the past 5–15 m.y. established a steep, eastward-dipping hydraulic gradient and a regional confined aquifer that extends downdip into the basin center (Senger et al.,

1987; Senger, 1991). Meteoric waters acquired their salinity as they entered the aquifer system by dissolution of halite along the upturned western flank of the basin margin (Fisher and Kreitler, 1987; Dutton, 1989). These meteoric waters descended below the halite dissolution zone and flowed laterally in the eastward-dipping strata, following the regional hydraulic gradient, and mixing with and displacing the more saline, connate evaporative brines in the basin center (Dutton, 1989; Bein and Dutton, 1993). In Pennsylvanian strata, the influx of meteoric waters is limited to the westernmost updip portion of this deep confined aquifer system (Bein and Dutton, 1993). Consequently, undisplaced connate evaporative brines in Pennsylvanian strata of the basin center are more saline (total dissolved solids = 70,000–215,000 mg/L; Stueber et al. 1998) than the meteoric-dominated waters (total dissolved solids = 2800–50,000 mg/L) in the Indian Basin and Dagger Draw reservoir complex, on the updip western limit of this regional aquifer system.

Our interpretation of west-to-east fluid flow based on the compositional and isotopic data for the Indian Basin and Dagger Draw formation fluids is thus consistent with regional fluid flow in the Permian basin confined aquifer system described by other workers (Fisher and Kreitler, 1987; Senger et al., 1987; Senger, 1991; Bein and Dutton, 1993). Although reservoir pressure data from Indian Basin and Dagger Draw fields are limited, the reservoir complex has a strong water

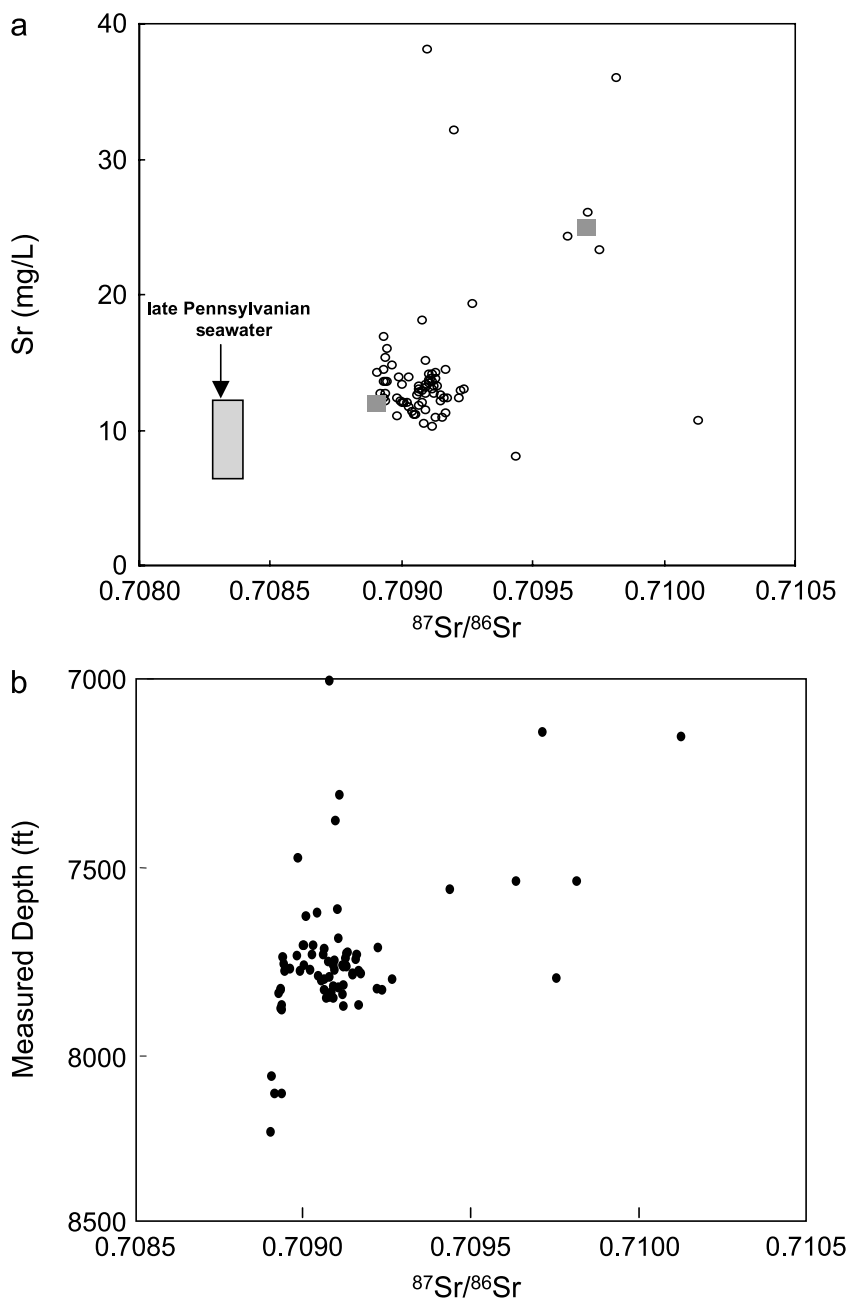


Figure 12. (a) Crossplot of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios vs. Sr concentrations of formation water samples. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of late Pennsylvanian seawater (normalized to NBS 987 = 0.710255) is from Burke et al. (1982), Popp et al. (1986b), and Denison et al. (1994). Strontium content of late Pennsylvanian seawater, 8 ± 2 mg/L, is based on modern seawater (8 mg/L). Gray rectangles indicate representative compositions of late Pennsylvanian seawater, least radiogenic brines, and most radiogenic brines used to illustrate mixing model in Figure 14b. (b) Plot of formation water $^{87}\text{Sr}/^{86}\text{Sr}$ ratios vs. mid-depth of perforations. Deepest samples have lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with less variability than shallower samples.

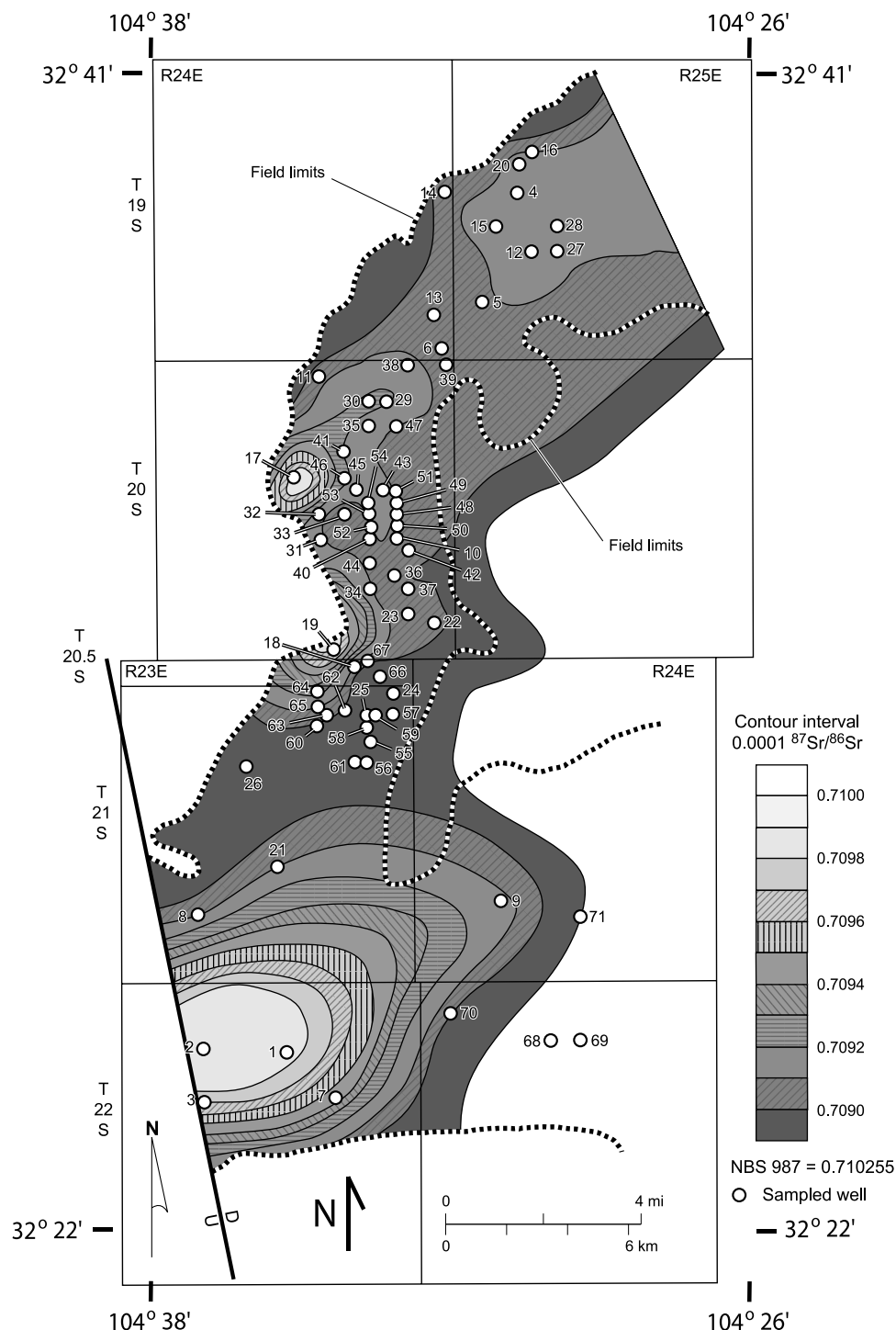
drive with a west-to-east downdip flow direction (Frenzel and Sharp, 1975). Regional formation water salinity trends for Pennsylvanian strata are poorly constrained in southeastern New Mexico. Salinity maps (McNeal, 1965; Bein and Dutton, 1993) contain no data from Eddy County, although both show a general west-to-east increase in salinity toward the basin center. For Indian Basin and Dagger Draw fields, this regional trend is reversed, with the most saline waters occurring at the updip southern and western portions of the field complex. Bein and Dutton (1993), however, acknowl-

edge that finer scale formation water compositional gradients are likely to be more complex than is implied by their regional model.

Origin of $^{87}\text{Sr}/^{86}\text{Sr}$ Compositions

Indian Basin and Dagger Draw formation waters have high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios relative to reported late Pennsylvanian marine values and the host rocks (Figure 8). Various workers (e.g., Stueber et al., 1984; 1987; 1998; Chaudhuri et al., 1987; Fisher and Kreitler, 1987;

Figure 13. Map of formation water $^{87}\text{Sr}/^{86}\text{Sr}$ distribution. Township and range outline is shown in Figure 1. The spatial patterns suggest multiple point source influx of ^{87}Sr -rich fluids in the updip southern and western portions of the reservoir and eastward flow down the hydraulic gradient into the Delaware basin.



Russell et al., 1988; Connolly et al., 1990; Chaudhuri and Clauer, 1993) have attributed enrichment in formation water ^{87}Sr to water-rock interactions with Rb-rich micas and clays and ^{87}Sr -rich K-feldspar in siliciclastic sediments at elevated diagenetic temperatures. It is well documented that water-rock interaction with siliciclastic and/or carbonate sediments will concomitantly

increase the $\delta^{18}\text{O}$ composition of the formation water (Clayton et al., 1966; Hitchon and Friedman, 1969; Kharaka et al., 1973, 1985; Land, 1980), moving it to the right of the meteoric water line. The δD and $\delta^{18}\text{O}$ composition of formation waters in Indian Basin and Dagger Draw fields coincide with meteoric values (Figure 11), indicating limited water-rock interaction

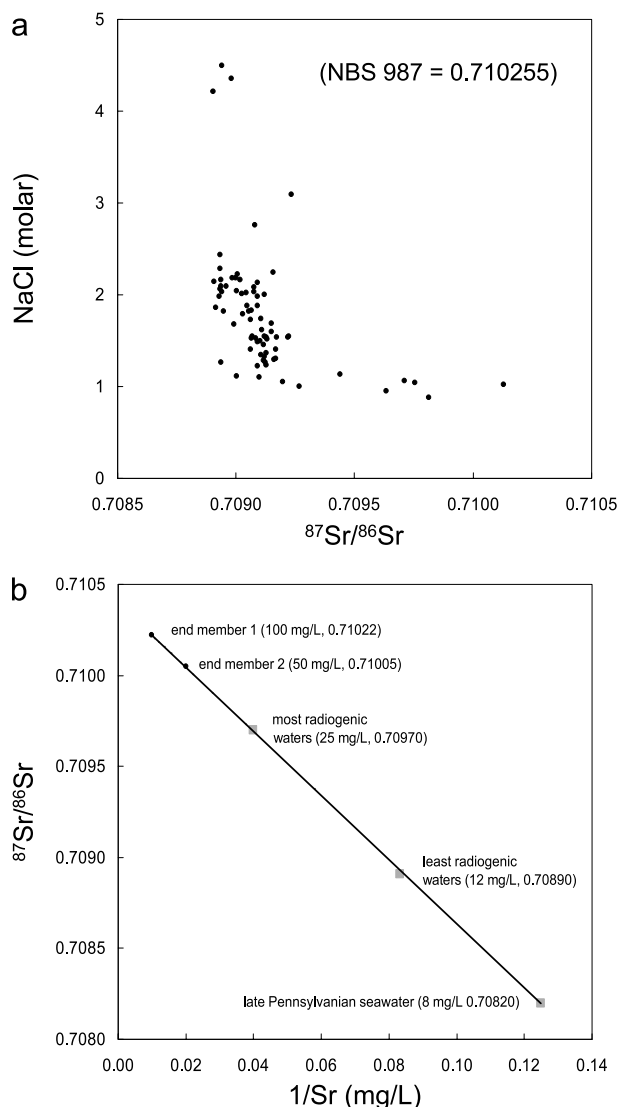


Figure 14. (a) Crossplot of formation water $^{87}\text{Sr}/^{86}\text{Sr}$ composition vs. Na/Cl molar ratio. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios increase as the Na/Cl molar ratio approaches 1:1 (i.e., salinity increasingly dominated by halite dissolution). This trend implies that the source of the solutes also is the source of radiogenic ^{87}Sr . (b) Crossplot of $1/\text{Sr}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$. Representative values for late Pennsylvanian seawater, least radiogenic present-day formation waters, and most radiogenic present-day formation waters form a hypothetical mixing line. The Sr composition of the source is defined by this line, extrapolated to higher $^{87}\text{Sr}/^{86}\text{Sr}$ values and lower $1/\text{Sr}$ ratios. The Sr composition of possible end members is depicted.

with siliciclastic or carbonate rocks. Moreover, the $^{87}\text{Sr}/^{86}\text{Sr}$ spatial trends (Figure 13) are inconsistent with derivation of ^{87}Sr from compactional dewatering of siliciclastic-rich basinal strata to the east.

The data display a trend of higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios as formation water Na/Cl molar ratios approach 1:1

(i.e., as the solutes increasingly are dominated by halite dissolution; Figure 14a). There is an analogous trend of lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with less variability with decreasing concentrations of total dissolved solids. These geochemical and isotopic trends imply that the source of radiogenic ^{87}Sr is the same halite and evaporites implicated as the source for the dissolved solids. Because halite beds in the Permian basin occur only in Upper Permian (Guadalupian and Ochoan) strata, derivation of ^{87}Sr from stratigraphically higher evaporites is consistent with the trend of higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios at shallower depths at the updip southern and western portions of the reservoir complex (Figures 12b, 13).

The Sr isotopic composition of Guadalupian-to Ochoan-age anhydrite and gypsum samples is 0.7069–0.7076 (Hovorka et al., 1993; Denison et al., 1998; Kirkland et al., 2000), normalized relative to NBS 987 = 0.710255. As expected, these $^{87}\text{Sr}/^{86}\text{Sr}$ values are consistent with Late Permian seawater, which ranged from 0.7067 to 0.7074 (Burke et al., 1982; Popp et al., 1986b; Denison et al., 1994), again normalized relative to NBS 987 = 0.710255. Consequently, the radiogenic ^{87}Sr in the Indian Basin and Dagger Draw formation waters must have come from evaporite minerals other than anhydrite or gypsum.

Naturally occurring ^{87}Rb decays to produce radiogenic ^{87}Sr with a half-life of 5.0×10^{10} yr (Faure, 1977). Because rubidium belongs to group IA, which includes sodium and potassium, and because the ionic radius of rubidium (1.48 Å) is similar to that of potassium (1.33 Å), rubidium readily substitutes for potassium in potassium-bearing evaporite minerals (Faure, 1977). Extensive, economically important deposits of potash (highly soluble potassium salts) occur in the McNutt Member of the Salado Formation in the Permian basin region (Figure 1). Driven by economic and scientific interests, these potash deposits have been the target of numerous investigations (Schaller and Henderson, 1932; Jones, 1954, 1972; Adams, 1969; Austin, 1980; Harville and Fritz, 1986; Lowenstein, 1988; Lambert, 1992; Barker and Austin, 1999). The McNutt potash zone ranges in thickness from 125 ft (40 m) in the western margin of the Delaware basin to more than 500 ft (150 m) in the basin center (Jones, 1972). To the west, deposits of soluble potassium minerals have been removed by groundwater solution (Austin, 1980; Griswold, 1982). The Salado Formation originally extended onto the northwestern shelf of the Delaware basin but has been eroded to the axis of the Pecos River Valley by dissolution (Gustavson and Finley, 1985).

Table 4. Comparison of Formation Water $^{87}\text{Sr}/^{86}\text{Sr}$ Compositions from Individual Wells Sampled at Different Times

Well Number	$^{87}\text{Sr}/^{86}\text{Sr}$ (original)	$^{87}\text{Sr}/^{86}\text{Sr}$ (resample)	Difference	Time Elapsed (months)
17	0.709635 \pm 10	0.709815 \pm 12	0.000180	19
40	0.709116 \pm 09	0.709127 \pm 09	0.000011	6
10	0.708998 \pm 09	0.709029 \pm 09	0.000031	25
14	0.709090 \pm 12	0.709068 \pm 13	−0.000022	5
43	0.709128 \pm 10	0.709119 \pm 10	−0.000009	6

Potash ore zones contain up to 100% potassium minerals, chiefly sylvite (KCl), carnallite ($\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$), polyhalite ($\text{K}_2\text{Ca}_2\text{Mg}(\text{SO}_4)_4 \cdot 2\text{H}_2\text{O}$), and langbeinite ($\text{K}_2\text{SO}_4 \cdot 2\text{MgSO}_4$) (Schaller and Henderson, 1932; Jones, 1954; Adams, 1969; Austin, 1980; Harville and Fritz, 1986). These highly soluble minerals contain up to 70 ppm Rb and have $^{87}\text{Rb}/^{86}\text{Sr}$ ratios as high as 330 (Tremba, 1973; Register and Brookins, 1980; Brookins et al., 1985). The high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (up to 0.7723 and higher) indicate that these thick deposits of Rb-rich potassium minerals are a potential source of radiogenic ^{87}Sr .

To evaluate the viability of an evaporite source for ^{87}Sr , strontium in two-component mixtures was modeled using principles outlined by Faure (1977). A mixing line (Figure 14b) in coordinates of $1/\text{Sr}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ can be fitted using the following assumptions: (1) late Pennsylvanian seawater $^{87}\text{Sr}/^{86}\text{Sr} = 0.70820$ and 8 mg/L Sr (same concentration as modern seawater); (2) a representative value for the least radiogenic brines (see Figure 12a) $^{87}\text{Sr}/^{86}\text{Sr} = 0.70890$ and 12 mg/L Sr; (3) more radiogenic waters, although highly variable (Figure 12a), we will use a value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.70970$ and 25 mg/L Sr (\approx average of the six most radiogenic samples). The hypothetical Sr composition of the source is defined by this model mixing line, extrapolated to higher $^{87}\text{Sr}/^{86}\text{Sr}$ values and lower $1/\text{Sr}$ ratios. Two of the possible end members are illustrated (Figure 14b). These $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are well within the range of reported values for Salado Formation evaporites (e.g., Tremba, 1973; Register and Brookins, 1980).

The average Sr contents of halite-rich Salado evaporite samples (>60% halite) is 73 ppm (Register and Brookins, 1980) to 165 ppm (Tremba, 1973); dissolution of 0.3 mol halite in 1 L water would yield 17,500 mg/L total dissolved solids with 22–50 mg/L Sr, comparable to the more saline water samples (Table 3). These calculations demonstrate that Salado Formation evaporite minerals are a viable source of radiogenic ^{87}Sr . The formation water Sr contents and $^{87}\text{Sr}/^{86}\text{Sr}$

values for Indian Basin and Dagger Draw, however, do not display a clear mixing relationship (Figure 12a), perhaps reflecting the highly variable Sr contents and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the evaporite mineral source (Tremba, 1973; Register and Brookins, 1980).

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.708676–0.709407 (normalized to NBS 987 = 0.710255) are reported by Stueber et al. (1998) for formation brines from Wolfcampian and Pennsylvanian carbonate reservoirs on the Central Basin platform; these brines were interpreted by the authors to be dominated by evaporatively concentrated Late Permian seawater with a smaller component of younger meteoric water. These waters are enriched in ^{87}Sr relative to both Late Permian seawater and their Wolfcampian to Pennsylvanian host carbonate reservoirs. The authors invoked a siliciclastic source for the radiogenic ^{87}Sr , although an evaporite source is also possible. Assuming that Ochoan evaporites had an initial $^{87}\text{Sr}/^{86}\text{Sr}$ composition of 0.7069 (Late Permian seawater) and that the potash minerals had an initial $^{87}\text{Rb}/^{86}\text{Sr}$ of 50–100 (consistent with data from Tremba, 1973; Register and Brookins, 1980), less than 5 m.y. is required to evolve a $^{87}\text{Sr}/^{86}\text{Sr}$ composition of 0.71005–0.71022 (the end-member examples in Figure 14b). The Ochoan is approximately 2.5 m.y. in duration (Harland et al., 1989), so it is reasonable to infer that the descending evaporative brines acquired their elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios by radioactive decay of ^{87}Rb in potassium-bearing minerals that were recrystallized and/or dissolved during early diagenesis and stabilization.

We propose that the formation waters in the Indian Basin and Dagger Draw reservoir complex acquired the bulk of their salinity through dissolution of halite and associated evaporite minerals, which also were the source of radiogenic ^{87}Sr . Meteoric dissolution of halite in the updip reaches of the Permian basin aquifer system is well documented (Fisher and Kreitler, 1987; Dutton, 1989; Bein and Dutton, 1993). Formation waters beneath halite dissolution zones are variably radiogenic (0.7073–0.7100) relative to Late Permian seawater (A. Dutton, 1987, personal communication;

summarized in figure 6 of Bein and Dutton, 1993). The well-defined $^{87}\text{Sr}/^{86}\text{Sr}$ compositional gradient in the Indian Basin and Dagger Draw (Figure 13) reflects the influx of evaporite-derived, radiogenic ^{87}Sr along the updip limit of the reservoir complex. The salinity trend of the formation waters is consistent with this interpretation. The highest salinities (up to 50,000 mg/L total dissolved solids) occur in the updip and southern and western portions of the field complex, and salinities decrease downdip toward the east (to 2800–5000 mg/L total dissolved solids).

Perhaps an analogous distribution in formation water $^{87}\text{Sr}/^{86}\text{Sr}$ compositions is reported for the Palo Duro basin (Fisher and Kreitler, 1987). Formation waters from two wells in the updip, western portions of the aquifer acquired their salinity from meteoric dissolution of halite; these waters are enriched in radiogenic ^{87}Sr relative to Permian seawater. Water samples from two wells in the downdip basin center are only slightly enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ relative to marine values (Fisher and Kreitler, 1987). The slight enrichment in $^{87}\text{Sr}/^{86}\text{Sr}$ values from basin center brines reported by Stueber et al. (1998) likely reflects buffering by their high Sr contents (124–525 mg/L) of marine-derived Sr (of probable Pennsylvanian to Permian origin). The low Sr contents (8–40 mg/L) of the Indian Basin and Dagger Draw formation waters make them susceptible to alteration to higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios by influx of radiogenic Sr from Rb-rich evaporite minerals associated with halite.

DISCUSSION

Regional to Local Fluid Flow

Formation water compositional and isotopic trends indicate that they originated from meteoric waters that recharged outcrops and shallow aquifers and acquired their salinity by dissolution of formerly overlying Upper Permian evaporites that are presently eroded to the axis of the Pecos River Valley. Deeply penetrating faults such as the Huapache fault (Hayes, 1964; Meyer, 1966) and associated splays (e.g., the normal fault bounding the southwest field limits; Figure 3) may have provided permeable conduits for the meteoric cross-formational flow to deeply buried Pennsylvanian strata (Figure 15). Incursion of meteoric water into Pennsylvanian rocks is limited to the westernmost portion of the deep-basin aquifer system (Bein and Dutton, 1993) because of the low permeability and considerable depth and

because Pennsylvanian rocks are not exposed to direct meteoric recharge in the Guadalupe Mountains region. The nearest Pennsylvanian outcrops lie approximately 100 mi (160 km) to the west, in the Sacramento and Hueco Mountains, where Pennsylvanian strata dip west into the Orogrande basin.

Downdip of the Indian Basin and Dagger Draw reservoir complex, formation waters in Pennsylvanian strata become increasingly more saline (McNeal, 1965; Bein and Dutton, 1993). Based on δD , $\delta^{18}\text{O}$, Na, Cl, and Br data, the brines are interpreted to be evaporatively concentrated Late Permian seawater (Dutton, 1987) that is being displaced by the influx of younger meteoric water following the regional hydraulic gradient that developed in response to topographic uplift during the past 5–15 m.y. (Dutton, 1987; Senger et al., 1987; Senger, 1991; Bein and Dutton, 1993). On the Central Basin platform, approximately 100 mi (160 km) to the east, formation waters in Wolfcampian and Pennsylvanian reservoirs are a mixture of evaporatively concentrated Late Permian seawater and younger meteoric water (Stueber et al., 1998). Apparently, these meteoric waters were transported via overlying, more permeable aquifers before descending to the Wolfcampian and Pennsylvanian strata (Stueber et al., 1998); alternatively, they may reflect leakage of shallow groundwater across confining Late Permian evaporites (Kreitler et al., 1985).

We interpret the formation water $^{87}\text{Sr}/^{86}\text{Sr}$ trends in Indian Basin and Dagger Draw fields to reflect west-to-east downdip flow, consistent with the west-to-east water drive indicated by the reservoir pressure data (Frenzel and Sharp, 1975), high water production, and displaced gas-oil-water contacts. Indian Basin and Dagger Draw represent the updip limits of the regional deep-basin aquifer system (Bassett and Bentley, 1982; Senger et al., 1987; Senger, 1991; Bein and Dutton, 1993). The spatial distribution of the formation water $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Figure 13) implies influx at multiple point sources along the updip field limits. These grade downdip to less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ waters, which coincide with $^{87}\text{Sr}/^{86}\text{Sr}$ values reported by Stueber et al. (1998) for formation waters dominated by evaporatively concentrated Late Permian seawater. It is possible that these less radiogenic formation waters represent the $^{87}\text{Sr}/^{86}\text{Sr}$ composition of the in-situ fluids that have been incompletely flushed by the younger meteoric waters. Numerical modeling of the Permian basin aquifer system demonstrates that the solute distribution responds more slowly to changes in hydraulic potential than fluid pressures, especially in the deep confined aquifer

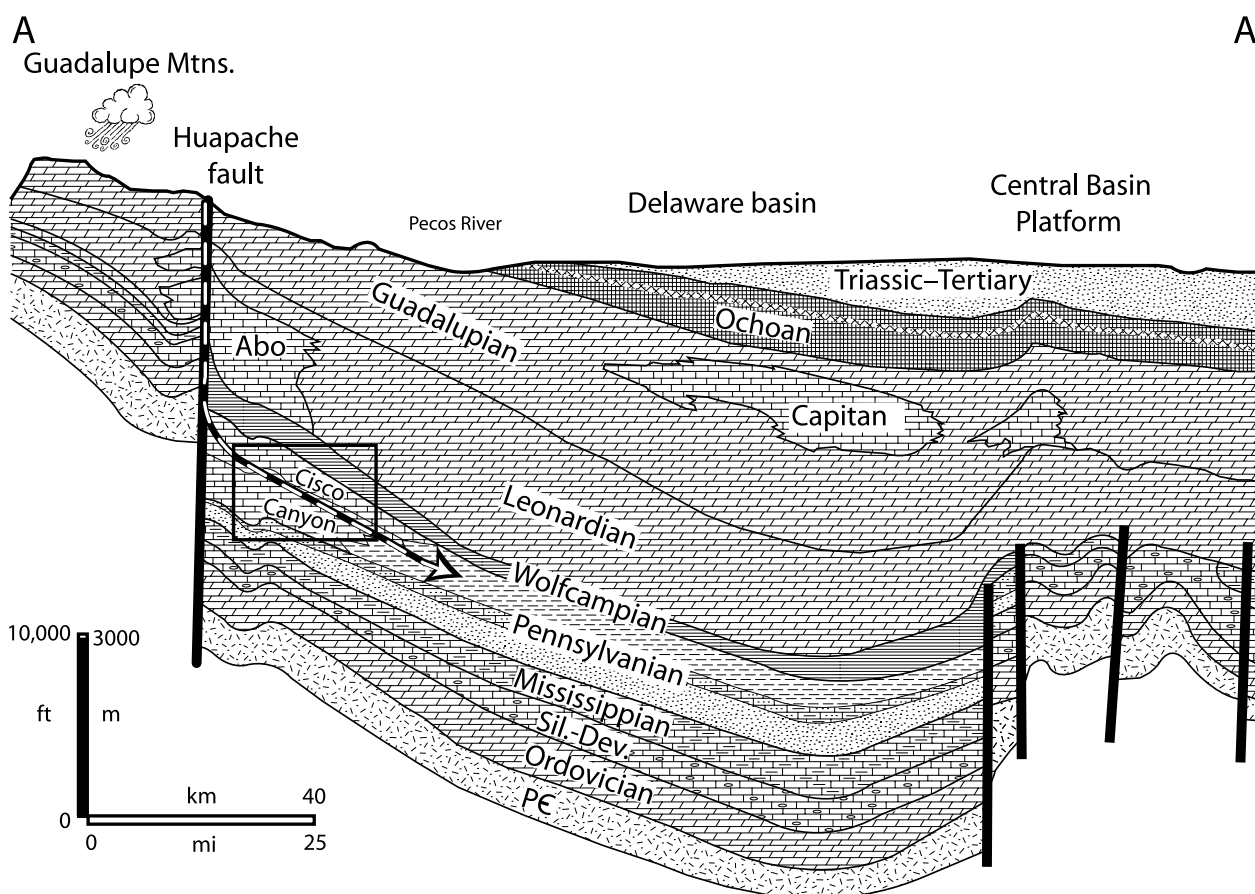


Figure 15. West-east structural cross section of Permian basin, line of section shown in Figure 1. The potentiometric gradient of the Permian basin aquifer system dips to the east, caused by topographic uplift in the Guadalupe Mountains. Canyon and Cisco reservoirs in the Indian Basin and Dagger Draw field complex are indicated by the rectangle. Geochemical and isotopic data indicate that formation waters are of meteoric origin and acquired their salinities and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from the dissolution of previously overlying Late Permian (Ochoan) Salado Formation evaporites, now eroded to the axis of the Pecos River Valley. These meteoric waters descended via cross-formational flow, possibly along the Huapache fault, to deeply buried Pennsylvanian strata; interpreted flow direction pathway is shown by the arrow.

(Senger, 1991). Consequently, in the Pennsylvanian strata, there has been insufficient time since topographic uplift in the past 5–15 m.y. for meteoric water to completely displace and flush the connate fluids (Dutton, 1987; Bein and Dutton, 1993).

The Sr isotopic trends in the Indian Basin and Dagger Draw reservoir complex record the initial influx of postuplift meteoric waters that derived their solutes from previously overlying Upper Permian evaporites. The compositional gradients of this paleoaquifer system reflect displacement and mixture of the in-situ formation fluids with younger meteoric waters of variable enriched $^{87}\text{Sr}/^{86}\text{Sr}$ compositions. This hydrogeochemical characterization of the Indian Basin and Dagger Draw reservoir complex constitutes a basis for evaluating future compositional perturbations associated with hydrocarbon production and waterflooding.

Implications of Formation Water Composition for Reservoir Characterization

Reservoir Connectivity and Fluid Flow

The paucity of reliable reservoir pressure data represents one of the major reasons for failing to predict reservoir behavior (Slider, 1983), especially for immature fields where pressure and production data are scarce. Although initial reservoir pressures can be determined from drillstem tests, these tests are not routinely run, and they commonly were not appropriately designed and implemented; moreover, the shut-in pressure must be extrapolated to obtain reservoir pressure. Consequently, pressure data commonly are sparse and have too much inherent error to quantitatively determine pressure gradients, reservoir continuity, and fluid flow. The actual reservoir behavior commonly becomes

apparent only after the field is on production, resulting in unanticipated costs associated with additional wells and inadequate surface facilities. The formation water composition provides a relatively inexpensive tool to interpret hydraulic communication among different zones or different regions of the reservoir and subsurface fluid flow.

Strontium isotopes are especially appropriate for formation water characterization because the Sr isotopic composition of a water sample collected at the well head is known to be identical to that of the subsurface fluid. The $^{87}\text{Sr}/^{86}\text{Sr}$ formation water compositional gradient in the Indian Basin and Dagger Draw reservoir complex is consistent with the strong water drive and west-to-east flow of meteoric-charged waters from the topographically elevated Guadalupe Mountains down dip into the Delaware basin. The hydrodynamic influence of meteoric water influx created developmental challenges in Indian Basin and Dagger Draw fields, including the high produced volumes of water and the structurally displaced and tilted gas-oil-water contacts.

Diagenetic Studies

Because diagenesis is a key factor in the porosity of carbonate rocks, understanding the diagenetic processes, timing, and distribution is essential to predicting the distribution of reservoir quality. Trace elements, stable isotopes, and Sr isotopes have been used by many workers to evaluate the origin and paragenesis of replacement dolomite and carbonate cements. The spatial variation in the $^{87}\text{Sr}/^{86}\text{Sr}$ composition of the present-day formation waters in the Indian Basin and Dagger Draw reservoir complex implies that coeval diagenetic minerals would have different $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, depending on their location. This leads to the concept of diagenetic facies for late burial fluids, analogous to those based on interpretations of the Mn and Fe contents of early meteoric calcite cements (e.g., Barnaby and Rimstidt, 1989). Consequently, interpretations that use $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to temporally correlate zones of late diagenetic carbonate cements from different locations should be viewed with caution.

SUMMARY AND CONCLUSIONS

The Indian Basin and Dagger Draw reservoir complex produces from upper Pennsylvanian shelf margin carbonates. Reservoir quality reflects both primary depositional fabric and intercrystalline and vuggy porosity

associated with burial dolomitization and dissolution. Vuggy pores are partially infilled by saddle dolomite and anhydrite cement.

Lime mudstones have $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ compositions that coincide with late Pennsylvanian marine values. Replacement dolomites and dolomite cements are depleted in ^{18}O , consistent with a burial origin at elevated temperatures. The $\delta^{13}\text{C}$ compositions of replacement dolomites and dolomite cements correspond with marine values, indicating that the $\delta^{13}\text{C}$ content of the dolomitizing fluids was buffered by marine carbonate.

The $^{87}\text{Sr}/^{86}\text{Sr}$ compositions of the reservoir host rocks (limestone, replacement dolomite, and dolomite and anhydrite cement) approximate late Pennsylvanian seawater values, indicating that marine-derived Sr dominated the diagenetic fluids. The present-day formation waters are not in isotopic equilibrium with the host rocks; they have higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and their δD and $\delta^{18}\text{O}$ compositions are diagnostic of Holocene meteoric waters that have not equilibrated with the host carbonate.

The brackish to saline formation waters contain 2800 to nearly 50,000 mg/L total dissolved solids. Covariant trends defined by their Na^+ , Cl^- , and Br^- contents and NaCl saturation index indicate that halite dissolution was the major source for the solutes; Ca^{2+} and SO_4^{2-} were derived from dissolution of anhydrite and gypsum associated with the halite-bearing evaporites. The formation waters, consequently, originated as meteoric waters that acquired their salinity through dissolution of overlying Upper Permian evaporites.

Formation water $^{87}\text{Sr}/^{86}\text{Sr}$ ratios exhibit a well-defined spatial distribution, with more radiogenic values (up to 0.710129) at the updip southern and western portions of the reservoir that grade down dip to less radiogenic waters (as low as 0.708903). The association of radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with higher salinity and increased dominance of halite dissolution on the solute composition implicates an evaporite source for the radiogenic ^{87}Sr . Because thick deposits of potassium salts in the Late Permian Salado Formation had high initial $^{87}\text{Rb}/^{86}\text{Sr}$ ratios, they are a prolific source of radiogenic ^{87}Sr for the saline waters derived from evaporite dissolution.

These meteoric-derived saline waters descended, perhaps along deeply penetrating faults, driven by topographic relief and by the density of the dissolved salts, to reservoir depths of more than 7000 ft (2100 m). The waters migrated into adjacent Pennsylvanian carbonate reservoirs and flowed eastward across the field complex, displacing and mixing with the in-situ formation fluids. Eastward-directed, down dip flow is

consistent with the regional hydraulic gradient, the strong water drive, the high volumes of produced water, and the tilted and displaced gas-oil-water contacts.

The Sr isotopic composition of formation waters can thus yield information for characterization of static reservoir properties such as reservoir connectivity, as well as dynamic processes such as subsurface fluid flow and water saturation. Because Sr isotopes in formation waters can exhibit considerable spatial heterogeneity, diagenetic studies that use Sr isotopes to temporally correlate late diagenetic mineral phases should be viewed with caution. Last, in basins with evaporites, formation water studies that use Sr isotopes must consider evaporites as a alternative source of ^{87}Sr to the commonly invoked siliciclastic source.

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